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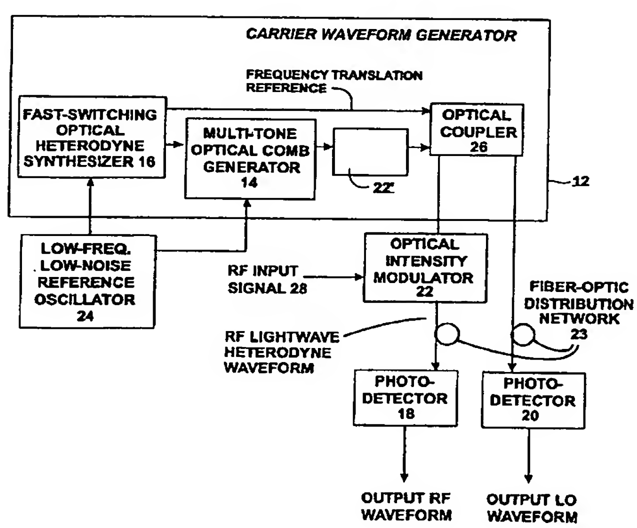
(54) Title: FREQUENCY AGILE SPREAD WAVEFORM GENERATOR AND METHOD AND PRE-PROCESSOR APPARATUS AND METHOD



(57) Abstract: A frequency agile spread spectrum waveform generator comprises a photonic oscillator andan optical heterodyne synthesizer. The photonic oscillator comprises a multi-tone opticalcomb generator for generating a series of RF comb lines on an optical carrier. The optical heterodyne synthesizer includes first and second phase-locked lasers; the first laser feedingthe multi-tone optical comb generator and the second laser comprising a wavelength-tunablesingle-tone or multi-tone laser whose output light provides a fequency translation reference.At least one photodetector is provided for heterodyning the frequency translation referencewith the optical output of the photonic oscillator to generate an agile spread spectrum waveform.

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Frequency Agile Spread Waveform Generator and Method and Pre-processor Apparatus and Method

Cross Reference to related Applications

This application claims the benefit of U.S. provisional application number 60/332,372 filed November 15, 2001 for an "Agile Spread Waveform Generator" by Daniel Yap and Keyvan Sayyah, the disclosure of which is hereby incorporated herein by reference.

This application is related to US provisional patent application entitled "Agile RF-Lightwave Waveform Synthesis and an Optical Multi-Tone Amplitude Modulator" bearing serial number 60/332,367 and filed November 15, 2001, and its corresponding US non-provisional application bearing serial number 10/116,801 and filed on April 5, 2002, the disclosures of which are hereby incorporated herein by this reference. These related applications are owned by the assignee of this present application.

This application is also related to US provisional patent application entitled "Injection-seeding of a Multi-tone Photonic Oscillator" bearing serial number 60/332,371 and filed November 15, 2001, and its corresponding US non-provisional application bearing serial number 10/116,799 and filed on April 15, 2002, the disclosures of which are hereby incorporated herein by this reference. These related applications are owned by the assignee of this present application.

This application is also related to US patent application entitled "Remotely Locatable RF Power Amplification System" bearing serial number 60/332,368 and filed November 15, 2001, and its corresponding US non-provisional application bearing serial number 10 /116,854 and filed April 15, 2002, the disclosures of which are hereby incorporated herein by this reference. These related applications are owned by the assignee of this present application.

This application is also related to a PCT application entitled "Agile Spread Waveform Generator and Photonic Oscillator" bearing serial number __________________, which

designates at least the United States and which was filed on the same date as the present application (Attorney Docket 620376-1), the disclosure of which is hereby incorporated herein by this reference. This related application is owned by the assignee of this present application.

Technical Field

This invention relates to a RF-lightwave waveform generator capable of generating a set of frequency-spread, frequency-hopped or frequency modulated RF waveforms. This invention also relates to a method and apparatus for pre-processing of such waveforms. The multi-tone waveform generated can further be amplitude-modulated with a pulse code and can serve as a Transmit waveform for a radar system. The pre-processor processes the Receive waveform or radar return signal. The pre-processing effectively creates multiple short pulses from a single long pulse and combines the information from those short pulses.

Background of and Information Regarding the Invention

A multi-tone, frequency hopped RF-lightwave waveform functions as a lightwave carrier for an optical transmission channel. The RF signal information carried by the optical transmission channel may be a pulse code, for example, which may be imposed onto the frequency-spread RF-lightwave carrier by means of a lightwave modulator. The final RF-lightwave waveform can be transmitted (by means of an optical fiber link or a free-space optical link) to a photoreceiver. The photoreceived signal, which is in electronic form (frequency converted and demodulated), can then be transmitted through a RF channel (an antenna or wireless link).

As is disclosed herein, the generator of the RF-lightwave carrier includes a frequency-comb generator that is coupled to an optical-heterodyne synthesizer. The comb is a set of RF tones amplitude-modulated onto a lightwave carrier. The generator of the RF-lightwave frequency comb is preferably a photonic oscillator, whose construction is known in the art. The optical heterodyne synthesizer is switchable and produces a pair of phase-locked, CW lightwave

lines (at two different optical wavelengths). One of these lightwave lines has the RF comb modulated onto it. Both lines, after being modulated by the comb, are then combined to generate the agile carrier. The center frequency of the photoreceived signal is the heterodyne beat note, which is the difference between the frequencies of the two lightwave lines produced by the optical heterodyne synthesizer. The wavelengths of these lines can be changed rapidly (the wavelengths of these lines can be changed with each transmit pulse, within a single transmit pulse or even within the transmission of a packet of data) to produce different beat-note frequencies. This process hops the center frequency of the resultant multi-tone RF lightwave carrier. Various known methods can be used to realize the optical heterodyne synthesizer.

One purpose of the agile frequency spreading and hopping is to make the resultant signal difficult for a non-coherent receiver to detect. Use of a frequency-spread carrier is one method to produce a signal that has Low Probability of Interception (LPI) by conventional intercept receivers. In addition, if the precise frequency of the carrier can be changed and is unknown to the interceptor, LPI performance is enhanced. These techniques are useful in LPI radar and communication systems.

Typically, an interceptor would use a wideband receiver that is channelized into smaller frequency bands to detect and identify the signal. If the signal falls within a single channel of the receiver, then it can be detected. However, if the signal is spread in frequency so those portions of it fall within many channels, it is difficult for the interceptor to distinguish that signal from the background noise. Typically, the channels of the intercept receiver may be scanned or long integration times may be used to sense an incoming signal. If the signal frequency is varied rapidly to hop between different channels within the sensing time, it again appears like noise. Alternatively, if the signal frequencies are varied rapidly with time although those hops lie within the received channels, that signal will be detected but difficult to identify. The dense, multi-tone waveforms that can be generated by the periodic frequency modulation embodiment can be designed to have a spacing that is smaller than the multi-tone waveform of the first (non-FM) disclosed embodiment, to defeat intercept receivers having finer channel spacings.

Another purpose of the frequency spreading is to make the signal less susceptible to jamming. The frequency coverage of the jammer may not be as large as the coverage of the

frequency-spread carrier. In addition, since the frequency-spread carrier consists of discrete tones that can be summed coherently, the signal power is used more efficiently. This is in contrast to the jammer, which is uniformly broadband. Rapid switching of the signal band also makes it less susceptible to being jammed, since the jammer cannot predict from one signal pulse to the next which frequency to jam.

In accordance with one aspect of the present invention, the generator applies a frequency modulation to a multi-tone RF carrier waveform. In one embodiment, a periodic electronic frequency modulation is combined with multi-tone generation by a photonic oscillator to produce a dense frequency-spread comb that has both fine comb spacing and large overall bandwidth. The density of this comb is greater than the density of combs generated with prior approaches. Such a dense, multi-tone Transmit waveform has an even lower probability of being detected by an electronic intercept receiver. A second embodiment combines frequency modulation by a single-value invertible (SVI) function with multi-tone generation by a photonic oscillator to encode different temporal portions of that waveform so that they are distinct from each other. Such a multi-tone frequency-encoded waveform can be combined with a suitable receiver to achieve temporal compression of a pulsed frequency spread comb. In another aspect of this invention, a pre-processor is disclosed for the return or Receive frequency-coded waveform that achieves pulse compression.

Previous methods to achieve LPI performance are based on using electronic synthesizers to produce the waveforms. Typically, a pulse-compression code is used to phase modulate a single-tone carrier and spread the spectrum. For example, if the signal pulse is 1 μsec wide and a 100-to-1 pulse compression code is used, a signal bandwidth of 100 MHz is obtained. The channel bandwidth of the interrogating receiver is typically much narrower than this. The bandwidth of present high-dynamic-range analog-to-digital converters is typically 100 MHz or less. Thus, interrogator channel bandwidths are also 100 MHz or less. This invention preferably makes use of the wideband nature of photonics to generate the frequency-spread waveforms. The total bandwidth of the comb can be quite wide, with several tens of GHz bandwidths easily achieved by the photonic methods of this invention. A pulse-compression code may be modulated onto the multi-tone comb, in addition to the signal information, to further spread the carrier. Prior art digital synthesizers which produce frequency-stepped waveforms typically have a bandwidth of less than 100 MHz. The switchable, optical-

heterodyne synthesizer disclosed herein is capable of a frequency range that exceeds 100 GHz.

Previous methods to generate multi-tone waveforms also are based on using electronic synthesizers to produce the waveforms. Multiple separate electronic synthesizers are used to produce only a small number of tones, which could cover a large bandwidth. Alternatively, frequency tunable electronic synthesizers could produce a waveform having a Fourier spectrum that contains a larger number of tones but over a much smaller bandwidth. The frequency of a single tone waveform has been modulated gradually or chirped for the purpose of pulse compression. Frequency modulation to compress a single tone pulse is common and large frequency excursions and pulse-compression ratios are possible. However, frequency modulation to compress a multi-tone pulse has been difficult to accomplish. Frequency modulation of a large number of tones has previously been too cumbersome and expensive to implement.

This invention makes use of the wideband nature of photonics to generate the dense frequency-spread, comb waveforms. The total bandwidth of the comb can be quite wide, with several GHz bandwidths easily achieved by the photonic methods of this invention. The finely spaced tones are produced by frequency modulation using an electronic method, which has fine frequency resolution. This invention also makes use of the properties of optical injection locking and heterodyning to frequency modulate a comb of many tones.

LPI waveforms typically have low instantaneous transmitted power. In order to increase the transmitted energy, a longer radar pulse may be used. However, long pulses have poor resolution of the target range, since returns that occur within a given pulse duration are not distinguishable. The Receive pre-processor of this invention improves upon prior methods of processing FM waveforms for achieving pulse compression and improved range resolution. Some of the prior methods mix the Transmit and Receive waveforms to compare them. A priori knowledge of the approximate target range is needed in order to synchronize those two waveforms. The pre-processor of this invention does not require a priori knowledge of the target range. Instead, it makes multiple time-delayed copies of segments of the Transmit reference waveform and repeatedly presents them for comparison with the Receive waveform.

Prior methods to process multi-tone waveforms involve using a bank of filters to spectrally separate those tones, which can then be processed individually. These methods can accommodate only tones of fixed frequency. In contrast, the pre-processor of this invention can accommodate a frequency modulated, multi-tone waveform.

The agile frequency spread waveform generator disclosed herein also is useful for communication systems with multiple users. Each user is assigned a particular and unique pattern for the frequency hops of the multi-tone waveform. A user can distinguish its signal from other signals that occupy the same band of frequencies by coherently processing the received signal with a copy of the particular waveform pattern of that user. This type of Code Division Multiple Access (CDMA) for lightwave waveforms is different from prior methods. The prior methods make use of short optical pulses, much shorter than the information pulse, whose wavelength and temporal location can be different for each user.

The prior art also includes:

1. A single-tone, single-loop optoelectronic oscillator - see US patent 5,723,856 issued March 3, 1998 and the article by S. Yao and L. Maleki, IEEE J. Quantum Electronics, v.32, n.7, pp.1141-1149, 1996. A photonic oscillator is disclosed (called an optoelectronic oscillator by the authors). This oscillator includes a single laser and a closed loop comprised of a modulator, a length of optical fiber, and photodetector, an RF amplifier and an electronic filter. The closed loop of this oscillator bears some similarity to the present invention. However, the intent of this prior art technique is to generate a single tone by incorporating an electronic narrow-band frequency filter in the loop. A tone that has low phase noise is achieved by using a long length of the aforementioned fiber. Demonstration of multiple tones is reported in this article achieved by enlarging the bandwidth of the filter. However, the frequency spacing of those multiple tones was set by injecting a sinusoidal electrical signal into the modulator. The frequency of the injected signal is equal to the spacing of the tones. This method causes all of the oscillator modes (one tone per mode) to oscillate in phase. As a result, the output of this prior art oscillator is a series of pulses. See Figure 14 (b) of this article.

2. A single-tone, multiple-loop optoelectronic oscillator - see US patent 5,777,778 issued July 7, 1998 and the article by S. Yao and L. Maleki, IEEE J. Quantum Electronics, v.36, n.1,

pp.79-84, 2000. An optoelectronic oscillator is disclosed that uses multiple optical fiber loops, as the time-delay paths. One fiber loop has a long length and serves as a storage medium to increase the Q of the oscillator. The other the fiber loop has a very short length, typically 0.2 to 2 m, and acts to separate the tones enough so that a RF filter can be inserted in the loop to select a single tone. The lengths of the two loops, as well as the pass band of the RF filter, can be changed to tune the frequency of the single tone that is generated. This approach teaches away from the use of multiple optical loops to obtain multiple tones, since it uses the second loop to ensure that only a single tone is produced.

3. 1.8-THz bandwidth, tunable RF-comb generator with optical-wavelength reference - see the article by S. Bennett et al. Photonics Technol. Letters, Vol. 11, No. 5, pp. 551-553, 1999. This article describes multi-tone RF-lightwave comb generation using the concept of successive phase modulation of a laser lightwave carrier in an amplified re-circulating fiber loop. The lightwave carrier is supplied by a single input laser whose optical CW waveform is injected into a closed fiber loop that includes an optical phase modulator driven by an external RF generator. This results in an optical comb that has a frequency spacing determined by the RF frequency applied to the phase modulator and absolute frequencies determined by the wavelength of the input laser. The loop also contains an Er-doped optical fiber amplifier segment that is pumped by a separate pump laser. The effect of the optical amplifier in the re-circulating loop is to enhance the number of comb lines at the output of the comb generator. One may expect some mutual phase locking between the different comb lines since they are defined by the phase modulation imposed by the external RF generator.

4. One technique for generating a RF signal is by optical heterodyning. See Figure 1. With this technique, the optical outputs of two laser wavelengths produced by a RF-lightwave synthesizer are combined onto a photodetector. In one simple case, the RF-lightwave synthesizer consists of two lasers each producing single wavelengths, i.e., single spectral lines. When their combined output is converted by a photodetector into an electronic signal (the photocurrent), that electronic signal has frequency components at the sum and difference of the two laser lines. Typically, the photodetector also acts as a low-pass frequency filter so that only the heterodyne difference frequency is produced. In order for the heterodyne output to be produced, the two laser lines must be locked together, so that their fluctuations are coherent. Various methods known in the art can be employed to achieve this locking. Optical heterodyning also can be combined with an external optical modulator to perform frequency

conversion (frequency translation). This function is illustrated in Figure 1. The dual-line lightwave output of the RF-lightwave synthesizer is supplied to an optical intensity modulator, with a typical modulator being a Mach-Zehnder interferometer. A RF input signal is also supplied to the modulator, which applies an intensity modulation onto the lightwave signal. The transfer function of the modulator results in the generation of frequency sum and difference terms. The output of the photodetector is another RF signal with frequency components that are the sum and difference between the frequencies of the RF input ω_{RF} and the frequency spacing between the two laser lines. In essence, the frequency difference ω_{LO} of the two laser-lines acts as a local-oscillator (LO) frequency that is multiplied with the RF input signal to produce an intermediate frequency (IF) $\omega_{LO} - \omega_{RF}$. A mathematical expression for this process is given as:

$$i_D = \frac{\alpha I_o}{2L_{MOD}}\left\{1 + m\sin(\omega_{RF}t) + M\cos(\omega_{LO}t + \phi) \pm \frac{1}{2}mM\sin\left[(\omega_{LO} \pm \omega_{RF})t + \phi\right]\right\}$$

where i_D is the photocurrent.

Brief Description of the Invention

In one aspect, the present invention provides an agile spread spectrum waveform generator comprising: a photonic oscillator comprising a multi-tone optical comb generator for generating a series of RF comb lines on an optical carrier; an optical heterodyne synthesizer, the optical heterodyne synthesizer including first and second phase-locked lasers, the first laser feeding the multi-tone optical comb generator and the second laser comprising a rapidly wavelength-tunable single tone laser whose output light provides a frequency translation reference; and a photodetector for heterodyning the frequency translation reference with the optical output of the photonic oscillator to generate an agile spread spectrum waveform.

In another aspect, the present invention provides a method of generating an agile spread spectrum waveform, the method comprising the steps of: generating multi-tone optical comb as a series of RF comb lines on an optical carrier; generating a wavelength-tunable single tone frequency translation reference; and optically combining the optical comb with the

frequency translation reference to generate a lightwave waveform suitable for subsequent heterodyning.

In yet another aspect this invention provides an apparatus for generation of frequency modulated, multi-tone waveforms (especially pulses) and an apparatus for pre-processing of such waveforms. The frequency modulated, multi-tone waveform generated can further be amplitude-modulated with a pulse code and can serve as a Transmit waveform for a radar system. The pre-processor processes the Receive waveform or radar return signal. The pre-processing effectively creates multiple short pulses from a single long pulse and combines the information from those short pulses.

According to the yet another aspect this invention of this invention, a generator applies a frequency modulation to a multi-tone RF carrier waveform. In one embodiment, a periodic electronic frequency modulation is combined with multi-tone generation by a photonic oscillator to produce a dense frequency-spread comb that has both fine comb spacing and large overall bandwidth. The density of this comb is greater than the density of combs generated with prior approaches. Such a dense, multi-tone Transmit waveform has low probability of being detected by an electronic intercept receiver. In another embodiment, frequency modulation by a single-value invertible (SVI) function is combined with multi-tone generation by a photonic oscillator to encode different temporal portions of the waveform so that the portions are distinct from each other. Such a frequency-encoded waveform can be combined with a suitable receiver to achieve temporal compression of a pulsed frequency spread comb. The generator can make use of the frequency selection property arising from the finite injection-locking bandwidth and short response lifetime of optical-injection locked lasers. A master laser is amplitude-modulated by an electronic frequency-modulated RF tone. Two slave lasers that are coupled to the master laser are biased to select, respectively, the optical carrier of the master laser and the RF-modulated sideband. The output of one slave laser has a wavelength that is modulated according to the electronic frequency modulation and represents the first RF-lightwave signal. The output of the other slave laser is fed to an optical comb generator, which amplitude-modulates onto that optical carrier a comb of tones. This second RF-lightwave signal is a frequency spread signal with tones separated by a coarse spacing but covering a large bandwidth. These two RF-lightwave signals are then combined by optically heterodyning them at one or more photodetectors.

For a periodic frequency modulation, the first signal has a Fourier spectrum that consists of a dense small-bandwidth comb. In contrast, the second signal has a coarse large-bandwidth comb. Optical heterodyning of multiple RF-lightwave signals incident on the photodetector is used to interlace the dense small-bandwidth comb (of Fourier spectral components) with the separate coarse large-bandwidth comb (whose tones are different modes of the photonic oscillator). The result is a multi-tone RF waveform that has a much larger number of tones than can be produced by conventional electronic frequency modulation alone, or by a multi-tone photonic oscillator alone.

For SVI frequency modulation, the optical-heterodyned signal is a comb of tones whose frequencies vary slowly and have a temporal variation that can be described by a SVI function. Thus, each temporal interval of the comb can be distinguished from each other temporal interval by the distinct frequencies of the tones at those times. Typically, the comb waveform is part of a long temporal pulse (or series of pulses). The frequency modulation makes the long comb pulse appear like a series of short adjoining comb pulses. If these pulses in the series are combined or overlayed together, the result is a time-compressed pulse.

In still another aspect, a Receiver contains a pre-processor that achieves pulse compression of the multi-tone waveforms. The pre-processing achieves temporal division of the multi-tone Transmit reference carrier waveform and the Receive (or radar return) waveform into series of segments. This feature permits multiple time-staggered sets of the Transmit reference segments to be made. These reference segments may then be used for comparison with the Receive waveform segments. By repeatedly presenting segments of the Transmit reference waveform for the comparison, a priori knowledge of the approximate radar target range (distance) is obviated. Yet another unique feature is the filters used to spectrally separate the multiple tones of the Transmit reference and Receive waveforms for their comparison by RF mixing. This comparison preferably occurs on a tone-by-tone basis or with small subsets of tones. These filters preferably have a periodic frequency spectrum. By using two sets of such filters with each set having a different spectral period, fewer filters are needed to accommodate the large number of distinct frequencies that must be separated. Also, a novel configuration of tapped delay lines and RF switches are preferably used to temporally align the Receive segments with the repeated Transmit-reference.

Description of the Drawings

Figure 1 is an illustration of a prior art frequency conversion technique performed with a RF-lightwave synthesizer;

Figure 2a is a block diagram of one embodiment of an agile waveform generator;

Figure 2b is a block diagram of another embodiment of an agile waveform generator;

Figure 3 is a block diagram of the multi-loop, multi-tone photonic oscillator;

Figure 4 depicts the measured RF spectrum of a multi-loop, multi-tone photonic oscillator;

Figure 5 is a detailed spectrum of one the RF tones of a dual-loop (1 km long loop, 8 m short loop) multi-tone photonic oscillator indicating a very high spectral purity;

Figure 6 is a block diagram of the multi-loop, multi-tone photonic oscillator with optically amplified loops;

Figure 7 is an illustration of fast-switching optical heterodyne synthesizer based on optical injection;

Figure 8 is an illustration of fast-switching heterodyne synthesizer based on a phase locked loop;

Figures 9 is a block diagram of the multi-loop, multi-tone photonic oscillator and a block diagram of the fast-switching optical heterodyned synthesizer consisting of a rapidly wavelength tunable and a fixed wavelength laser, the photonic oscillator having a fiber length control apparatus and a feedback loop to control the fiber lengths; and

Figure 10 is similar to Figure 9, but instead of having a fiber length control apparatus, it utilizes phase control of the loop to compensate for environment changes in the lengths of the fibers in the multi-loop, multi-tone photonic oscillator.

Figure 11 is a block diagram of the laser modulator and selector shown in Figure 2b;

Figures 11a – 11c illustrate the generation of the frequency-modulated tones by the apparatus of Figure 11;

Figure 12 is a block diagram showing elements of Figure 11 with the photonic oscillator of Figure 3;

Figures 13a – 13d depict frequency spectra produced at various locations in the waveform generator;

Figures 14a – 14c illustrate various frequency-modulated spread waveforms that can be generated;

Figure 15 is a block diagram illustrating a switched and tapped delay-line preprocessor for the frequency modulated waveform of Figure 14c;

Figure 16 is a block diagram illustrating multi-tone comparator functions for the pre-processor; and

Figure 17 illustrates a first stage of a preferred delay-line pre-processor for multi-tone generation.

Detailed Description

Before describing the details of the present invention, some relevant background information is provided on the generation of a RF signal by optical heterodyning. With this technique, illustrated by Figure 1, the optical outputs of two lasers at different wavelengths are combined onto at least one photodetector. In a simple example, each of the two lasers produces a single wavelength (i.e. a single optical frequency, spectral tone or spectral line). When the combined output of these two lasers is converted by the at least one photodetector into an electronic signal (the photocurrent), that electronic signal has frequency components

at the sum and difference of the two laser lines. This occurs because the photodetector current is proportional to the incident optical power (or the square of the electric field of the incident light). The sum frequency is a very high, optical frequency. The difference frequency is typically in the RF range and is output from the photodetector as a current or voltage. In order for the heterodyne output to be produced, the two laser lines are locked together, so that their phase fluctuations are coherent. Various techniques known in the art can be employed to achieve this locking. The preferred technique used herein is to optical-injection lock both lasers (called the slave lasers) to different phase-locked tones (or spectral lines) that are emitted by a third laser (called the master laser). One or both of the two tones that are output from the two slave lasers can be supplied to an optical intensity modulator, with a typical modulator being a.Mach-Zehnder interferometer. A RF input signal may also be supplied to the modulator, which, if used, applies an intensity modulation onto the lightwave signal. The transfer function of the modulator results in the generation of additional frequency sum and difference terms. The output of the at least one photodetector is then another RF signal containing frequency components that are the sum and difference between the frequencies of the RF input and the frequency spacing between the two laser lines. In essence, the frequency difference of the two laser-lines acts as a local-oscillator (LO) frequency that is multiplied with the RF input signal to produce the output signal. Typically, the at least one photodetector also can be used with electronic bandpass or low-pass filters, or the at least one photodetector itself can act as a low-pass frequency filter, so that only the desired range of output frequencies is selected.

This invention relates to a unique approach in the generation of rapidly frequency hopped or dithered, or frequency modulated multi-tone RF comb lines using coherent optical heterodyning in order to make the signal transmitted on such carriers difficult to detect. In the following description of the invention, the concept of optical heterodyning is discussed first, to provide background information. Two embodiments are disclosed by Figures 2a and 2b. Figure 2a is particularly useful in a frequency hopped environment (although it can be adapted for use in a frequency-modulated environment instead), while the embodiment of Figure 2b is particularly useful use in a frequency-modulated environment. Frequency modulation of the RF comb lines can further increase the resistance of the transmitted signals being subject to detection and/or can improve range detection capabilities of radar signals.

Two embodiments for generating a frequency translatable comb signal are described with reference to Figures 3 - 6. Then, several embodiments for producing a frequency-hopped waveform for the embodiment of Figure 2a are described with reference to Figures 7 and 8. Modifications for improved stability are discussed (with reference to Figures 9 - 10) to one of the two embodiments for generating the frequency translatable comb signal.

Figures 11 – 13 relate to the embodiment of Figure 2b, while Figures 14a – 17 relate to its related pre-processor.

The block diagram of one embodiment of an agile waveform generator 12 is shown in Figure 2a. It has two main portions 14, 16 that will be described in greater detail with reference to Figures 3 and 6 - 10. The first main portion is a type of photonic oscillator, namely, a multi-tone optical comb generator 14 that generates a series of low-phase-noise RF comb lines on an optical carrier. The second main portion is a fast-switching optical heterodyne synthesizer 16, which includes two phase-locked lasers 70, 72 (see Figures 7 and 8), the first laser 70 feeding the optical comb generator 14. The second laser 72 is a rapidly wavelength-tunable single tone laser whose output light, a frequency translation reference, is heterodyned with the optical output of the photonic oscillator 14 in a photodetector 18 to generate the frequency hopped RF comb lines (sometimes element 14 herein is referred to as an oscillator and sometimes as a generator - this is due to the fact that "oscillator" 14 "generates" the RF comb). Local oscillator (LO) selector 80 controls the frequency hoping. The agile wavelength offset of the two lasers determines the translation in frequency of the resulting multi-tone RF comb. Furthermore, an optical phase modulator (not shown) can also be inserted in the optical path of the wavelength tunable laser, which can result in further dithering of the multi-tone RF comb in the frequency domain. This effect, combined with the frequency hopping mechanism described above, renders the modulated RF transmit signal very difficult to intercept.

An optical coupler 26 combines the output of the comb generator 14 with the output of the wavelength tunable laser in synthesizer 16. The combined output can be modulated by the RF transmit signal 28 using an optical intensity modulator 22 as shown in Figure 2a. In Figure 2a the optical intensity modulator 22 is shown downstream of the optical coupler 26. Alternatively, the optical intensity modulator 22 can be placed between generator 14 and coupler 26 as shown by block 22'. Moreover, the output of coupler 26 can be further

modulated by additional pulsed or polyphased codes (or the transmit signal can be modulated by such codes) to reduce the probability of detection (intercept) even more. The pulsed or polyphased codes can be applied at the RF signal input 28 or at a separate optical intensity modulator in series with modulator 22).

A second output of the optical coupler 26 can be used to generate a local-oscillator reference signal from a photodetector 20, which can be conveniently employed in a coherent receiver. An alternate embodiment is to have the RF input signal 26 and any additional codes modulate the output of the comb generator 14 before the modulated output is combined with the frequency translation reference in coupler 26 by moving the optical intensity modulator(s) discussed immediately above upstream of coupler 26 as depicted in Figure 9.

The low frequency low noise reference oscillator 24 provides a timing reference signal to the synthesizer 16 and to the multi-tone oscillator 14.

The modulated frequency hopped RF comb lines available at the output of photodetector 18 are applied to a suitable RF amplifier (not shown) and thence to an antenna (also not shown) for transmission as a communication signal or as a radar pulse, as appropriate to the application in which the present invention is utilized.

Photodetector 18 can be implemented as a portion of the RF amplifier and therefore the RF Lightwave Heterodyne Waveform available from, for example, modulator 22, can be supplied as an optical signal to the RF amplifier. One possible embodiment for an RF amplifier is disclosed in US provisional patent application entitled "Remotely Locatable RF Power Amplification System" bearing serial number 60/332,368 and filed November 15, 2001, and a corresponding non-provisional application bearing serial number 10/116,854 and filed on April 15, 2002. The RF Lightwave Heterodyne Waveform could be applied as the sole input to fiber 113 depicted on Figure 2 of that application and then the function of photodetector 18 would be provided by detectors 302 shown on Figure 2 of that application. If the output of photodetector 18 is utilized as an input to the RF amplifier, as disclosed in the US patent application entitled "Remotely Locatable RF Power Amplification System" noted above, then the output of photodetector 18 could be applied as an input to modulator 106 shown on Figure 2 of that application.

A block diagram of another embodiment of a frequency-modulated, spread waveform generator is shown in Figure 2b. This embodiment preferably consists of three main segments. The first segment 17 generates a lightwave carrier for the second segment 13 and also a RF-lightwave signal, whose frequency is modulated. If the frequency modulation is periodic, the Fourier spectral components of this signal comprise a multi-tone comb. The tone spacing of this first comb is quite fine, typically in the range of 0.1-100 MHz. The second segment 13 generates a set of low-phase-noise RF comb lines on the lightwave carrier, supplied to it by the first segment 17. The second segment 13 also places both RF-lightwave signals (i.e., the resultant RF-lightwave heterodyne waveform) onto the same optical fiber. The third segment 15 provides a way to apply an electrical encoding or blanking waveform, such as a radar pulse code or a communications signal, onto the RF-lightwave waveform. The third segment 15 also generates both a RF-output Transmit waveform and a RF reference waveform by optical heterodyning the two RF-lightwave signals at photodetectors 18, 20. The output Transmit waveform is the encoded LPI waveform that is to be transmitted from the antenna of the sensor system. The reference carrier waveform can be an un-encoded wideband RF comb (as shown in Figure 2b), which can be used by a matched or coherent receiver of the sensor system. The reference carrier waveform also could be encoded by means of the same optical intensity modulator as the Transmit waveform or with a different modulator.

The RF-lightwave multi-tone comb generator 14 of the embodiments of either Figures 2a or 2b can be implemented using a variety of techniques. One embodiment is a multi-loop, multi-tone photonic oscillator 14, a block diagram of which is shown in Figure 3 (an additional block diagram, including additional features, will be discussed later with reference to Figures 6, 9 and 10). The multi-loop, multi-tone photonic oscillator 14 includes at least two loops that preferably have a common portion. An optical modulator 32 is preferably employed in the common portion while lightwave delay paths 34 and 36 and photodetectors 38 and 40 are employed in respective first and second loops. A low-noise electrical amplifier 42 and a RF bandpass filter 44 are preferably also deployed in the loops common portion. The laser light is preferably provided by a laser 70, which supplies the power for the oscillator 14, the laser light being modulated by a RF signal at the electrical input 33 of the modulator 32. The modulated lightwave is then split into two branches, one connected to a shorter optical delay path 34, and the other to a longer optical delay path 36. The optical signals in the two lightwave paths are sensed by two photodetectors 38 and 40 whose electrical outputs are

combined and, following amplification and bandpass filtering, are fed back to the modulator 32, as shown in Figure 3. The bandpass filter 44 sets the bandwidth of the generated RF multi-tone comb spectrum. The two photodetectors 38, 40 can be replaced by a single photodetector (see detector 39 in Figure 10).

The operating principle of this multi-tone oscillator 14 is as follows. Random electrical noise generated in the feedback loops modulates the laser light, which after propagating through the two optical delay paths 34 and 36 and being photodetected is regeneratively fed back to the modulator 32. This positive feedback results in oscillations if the open loop gain is greater than one. If need be, an amplifier 42 may be provided in the loop common portion to add gain. Gain can alternatively be added in the optical loops by using a pump laser (of the type shown, for example, in Figure 6 - see element 29). In the case of a dual-loop photonic oscillator, potential oscillation modes exist at frequency intervals that are an integer multiple of the inverse of the delay times of the two loops (τ_S and τ_L), where τ_S is the delay time of the shorter loop and τ_L is the longer loop's delay time. However, oscillation generally will only occur at frequencies where the modes resulting from both delay loops overlap, if the sum of the open loop gains of both feedback loops is greater than one and the open loop gains of each feedback loop is less than one. Therefore, oscillation will only occur at modes spaced at the frequency interval determined by the shorter loop ($\Delta f = k/\tau_S$). On the other hand, the oscillator phase noise $S(f')$ decreases quadratically with the optical delay time in the longer loop: $S(f') = \rho/[(2\pi)^2(\tau_L f')^2]$, where ρ is the input noise-to-signal ratio and f' is the offset frequency. Combining these two effects results in a multi-tone, multi-loop photonic oscillator in which the tone spacing and phase noise can be independently controlled.

The measured RF spectrum of a dual-loop, multi-tone photonic oscillator spanning a frequency range of 1 GHz is shown in Figure 4. This oscillator has two fiber optic delay loops, with a shorter loop of about 8 m (or longer) and a longer loop of about 1 km (or longer). When the length of the shorter loop is 8 m, the tone spacing is about 26 MHz, indicating a delay time of 38 nanoseconds. The detailed RF spectrum of one of the oscillation tones in the dual-loop multi-tone photonic oscillator is shown in Figure 5, indicating an excellent spectral purity. The frequency span is 5 KHz. The length of the longer loop is preferably at least forty or more times longer than the length of the shorter loop.

In another embodiment, the multi-tone photonic oscillator 14 can be implemented using optical amplifiers, as shown in Figure 6, instead of electronic amplifiers, as previously discussed with reference to Figure 3. In this embodiment, each loop preferably includes an isolator 25, an Er-doped or an Yb/Er-doped fiber segment 27, and a wavelength division multiplexer (WDM) 31. Each doped fiber segment 27 is preferably pumped by a pump laser 29, although the pump laser 29 and the associated Er-doped or Yb/Er-doped segment 27 could be employed in only one of the loops, if desired. The isolators 25 keep the light flowing in the correct direction (clockwise in Figure 6) in the loops and also keep the light from the pump laser 29 from interfering with the operation of the modulator 32. The WDMs 31 couple the light from the pump laser 29 into the loops and keep that light from interfering with the function of the photodetectors 38, 40. The two photodetectors 38, 40 may be replaced with a single photodetector 39 as shown in Figure 10 if desired, and two pump lasers 29 could be used (one for each loop), if desired.

An improvement which provides for a more level output across the comb of Figure 4 is disclosed in the aforementioned PCT application entitled “Agile Spread Waveform Generator and Photonic Oscillator”. The reader is directed to the disclosure of that application to learn how the comb generators 14 of Figures 3, 6 and 9 may be modified to flatten the comb’s amplitude.

Several techniques can be used to realize the fast-switching optical heterodyne synthesizer 16 of Figure 2a. See Figures 7 and 8 for exemplary embodiments. In the embodiments of Figure 7 and 8, the synthesizer 16 includes the two previously mentioned lasers 70 and 72. These lasers are phase-locked, as previously discussed. One laser 70 is a fixed wavelength laser and the other laser 72 is a rapidly tunable laser. This phase locking can be accomplished using several known techniques. One of these techniques, and the preferred technique, is illustrated in Figure 7. This technique involves optical injection locking of the two lasers 70 and 72 (the slave lasers) to different lines of a multiline master laser 76. These lines can be: (1) different modes of a mode-locked master laser, (2) modulation sidebands of a frequency modulated master laser, or (3) different phase-locked modes of a multiline laser (see the comb generator disclosed by prior art references 1 and 3).

A highly stable and low phase-noise, single tone RF reference oscillator 78 may be used to externally lock the mode locked laser 76 (if using alternative 1 mentioned above), frequency

modulate the master laser 76 (if using alternative 2 mentioned above), or phase modulate the multiline laser 76 (if using alternative 3 mentioned above). The RF reference oscillator 78 may be further stabilized or synchronized by an additional reference oscillator 24 as discussed with reference to Figure 2a.

The optical output of the multi-tone comb generator 14, which is fed by the fixed wavelength laser 70, is an optical comb containing the laser wavelength modulated by the RF comb lines Combining this optical comb with the rapidly tunable wavelength of the second laser 72 in photodetectors 18 or 20 results in a set of RF comb lines which can be rapidly switched (hopped) in the frequency domain. The frequency-hopping interval is determined by the wavelength interval over which the second laser 72 is stepped. With the optical injection locking approaches described above (see the embodiment of Figure 7), this interval is determined by the spacing between adjacent modes or sidebands of the multiline master laser 76. If the mode spacing for the multiline master laser 76 is 5 GHz, and the bandwidth of the comb is 4 GHz, the center frequency of the comb can be hopped rapidly between 5 GHz and 10 GHz and 15 GHz, and so on, in any order. Since these two lasers 70 and 72 are phase-locked, as described above, the resulting frequency-switchable heterodyned RF tones will have good spectral purity and low phase noise. Note should be made of the fact that the frequency-hopping interval can be smaller than the bandwidth of the comb.

Another technique for phase locking laser 70 and 72 involves a phased locked loop (see Figure 8).

The phase-lock loop embodiment of Figure 8 takes the heterodyned output of the two lasers 70 and 72 and compares that output with an external RF reference 82 in a RF phase detector to produce an error signal 90 at the output of a mixer 86 for correcting the wavelengths of the lasers 70, 72. The outputs of the two lasers 70, 72 are coupled by coupler 85 and detected by photodetector 87 where the heterodyned electrical signal is produced. The output of detector 87 is preferably frequency-divided down by a frequency divider 84 and the output of the frequency divider 84 is applied to the mixer 86, which acts as a phase detector. With this approach, the wavelength difference between the two phase-locked lasers 70, 72 can be varied in steps equal to the steps of the frequency divider 84. If continuous tuning is desired then the RF reference 82 should be continuously tunable. A variation of the phase-locked loop approach involves using wavelength intervals that are larger than the frequency of the

RF reference. The frequency divider 84 divides the heterodyne output of the two lasers to a lower frequency that can be compared with the RF reference 82 by mixer 86, as illustrated in Figure 8. The frequency-hopping interval would then be equal to the divider ratio multiplied by the minimum step of the tunable RF reference 82. The embodiment of Figure 8 permits the hopping to be very fine, so fine that the signal seems essentially continuous. The output 27 of the coupler 85 has hopping information useful to an associated receiver when used in a radar application, for example.

The phase-locked loop embodiment of Figure 8 can be adapted to impose a frequency modulation on the sidebands (as is done with the various embodiments discussed with reference to Figures 2b and 11-13) by implementing oscillator 82 as a VCO.

These four alternatives (the three alternative discussed with reference to Figure 7 and the alternative of Figure 8) have different advantages and disadvantages. Generally speaking, alternative (1) (which is associated with Figure 7) generates very clean tones that are easy to switch between. Alternative (2) yields fewer tones. Alternative (3) yields a large number of tones, but they are not clean. Alternative (4) requires lasers that have either a very narrow linewidth or a phase locked loop with a very short loop delay time.

The LO selector 80 shown in Figure 7 adjusts the free-running frequency or wavelength of laser 72 to match the desired line output from multiline master laser 76. This is accomplished by setting the temperature and drive current of laser 72. The LO selector 80' shown in Figure 8 sets the temperature of laser 72 to obtain a desired free-running frequency or wavelength for that laser. The actual laser frequency or wavelength is fine tuned by controlling its drive current by means of the phase lock loop. LO selector 80' also selects the frequency of the tunable oscillator 82 as well as the divide ratio of the frequency divider 84.

Figure 9 is a block diagram of the multi-loop, multi-tone photonic oscillator 14, the photonic oscillator having a fiber length control apparatus 92 and a feedback loop to control the fiber lengths of delay lines 34 and 36. The delay lines 34 and 36 are apt to be sufficiently long that as they change length in response to changes in temperature of their environment, the change in temperature will adversely affect the phase of the oscillator 14. Thus, some means for compensating or controlling the tendency of the fibers 34 and 36 to change length in response to changes of environmental temperature is desirable. In Figure 9 fiber length control

apparatus 92 may be a heating and/or cooling apparatus for heating and/or cooling at least the fibers 34 and 36 in order to control their lengths or optical refractive index. Alternatively, fiber length control apparatus 92 may physically stretch or strain the fibers 34 and 36 in order to control their lengths or optical refractive index. For example, fiber length control apparatus 92 can comprise piezoelectric fiber stretchers. A feedback circuit preferably comprising a frequency divider 94, a tone select filter 96, a mixer 98 and a filter 100 is utilized to control apparatus 92. The tone select filter 96 selects one of the generated tones output from modulator 32' and the frequency divider 94 divides down the selected tone for comparison, by mixer 98, against a reference tone available from, for example, reference oscillator 24. The output of mixer 98 is filtered to remove unwanted mixing products and then applied as a control signal to fiber length control apparatus 92. In that way, the lengths of the fibers 34 and 36 are adjusted in response to changes in one of the frequencies generated by the photonic oscillator 14.

The optical intensity modulator of the embodiment shown in Figure 9 is preferably implemented as an electro-absorption modulator 32'. An electro-absorption modulator 32' not only modulates the amplitude of the lightwave carrier supplied by laser 70 but it also produces a photocurrent 93 that is fed to the frequency divider 94 in the feedback circuit. Alternatively, the feedback from the loops may be obtained at the outputs of the photodetectors 38, 40. Also, the two photodetectors 38, 40 may be replaced by a single photodetector 39 as shown in Figure 10.

Figure 10 is similar to Figure 9, but instead of having a fiber length control apparatus 92, it utilizes phase control of the loop to compensate for environmental changes in the lengths of the fibers 34, 36 in the multi-loop, multi-tone photonic oscillator 14. An electrical phase shifter 91 is placed in the multi loops of the multi-tone comb generator 14 and is utilized in lieu of the fiber length control apparatus 92 to compensate for changes in the lengths of fibers 34 and 36. The feedback circuit of Figure 9 is used to control the electrical phase shifter 91. This feedback circuit taps off a portion of the photodetected and amplified multi-tone waveform to determine its departure from the frequency and phase of the reference oscillator 24.

Only one photodetector 39 is depicted receiving the light from loops 34 and 36 in Figure 10. This is only an apparent simplification. One photodetector 39 might seem simpler than two

photodetectors 38, 40, but the use of one photodetector 39 will usually require tight phase control between the two loops (to fractions of the optical wavelength) so that an out-of-phase condition between the two loops does not cause the light to sum incorrectly (or even cancel). Thus, the use of two photodetectors 38 and 40, one associated with each delay line 34 and 36, is preferred for all embodiments, including the embodiment of Figure 10.

The multi-tone, optical comb generator 14 can alternatively be of a prior art design, such as that disclosed by reference 1 or even possibly reference 3 mentioned above. Such a design is not preferred because of its non-continuous output.

Injection seeding of the photonic oscillator 14 may be needed to initiate oscillations in multiple tones. A suitable injection seeding scheme is disclosed in the US patent application entitled "Injection-seeding of a Multi-tone Photonic Oscillator" referred to above.

The implementations and functions of the various components shown in Figure 2b are described next. Figure 11 shows a block diagram of the frequency-modulated-tone or fine-spaced-comb generator 17 that comprises the first segment of the waveform generator. This generator 17 contains a frequency modulated RF oscillator 30 and also a laser modulator – selector 16'. The laser modulator – selector 16' is comprised of at least three lasers. One of the lasers is the master laser 23 and the other two lasers are the slave lasers 70, 72. The optical output of the master laser 23 is injected into the two slave lasers 70, 72. The light from the master-laser 23 optically injection locks the slave lasers so that the light emitted from a slave laser has the same frequency content as the injected light that is within the injection-locking bandwidth of the slave laser. The frequency modulated RF oscillator 30 comprises an oscillator that produces a single RF tone and a means to frequency modulate this RF tone. Such means are known in the art (e.g., a VCO). For a periodic frequency modulation, a large FM index is desired in order to produce a Fourier spectrum that consists of many spectral sidebands. The intensities of the sidebands depend on the waveform shape used for the frequency modulation. The types of waveform shapes and their resulting modulation-sideband spectra are also known per se in the art. For example, some periodic frequency chirps can produce sideband spectra having tones of uniform intensity. The center of these sidebands typically has a frequency of several GHz to several tens of GHz. The preferred extent or bandwidth of the FM sidebands depends on the application needs and the

electronic components available to produce the frequency modulated RF waveform. This bandwidth typically is in the range of 10-500 MHz.

The frequency-modulated RF signal produced by the RF oscillator 30 is used to amplitude-modulate the master laser 23. This laser 23 preferably emits in a single optical wavelength, when it is not modulated. The master laser can be a single laser whose current is modulated by the frequency-modulated RF signal. The result is a fixed-tone optical carrier (the un-modulated laser wavelength) and a pair of modulation sidebands whose frequencies change with time (See Figure 11a). The master laser 23 also can comprise a laser and a separate modulator. In that case, the frequency-modulated RF signal is generally applied as a voltage that changes the intensity of light passed through the modulator. Thus, the laser produces a fixed tone and the modulator applies the modulation sidebands. Both direct modulation of a laser and use of a laser with a separate (external) modulator are well known techniques for amplitude modulation of laser light.

The output wavelength spectrum (from which the frequency spectrum can be derived) of the master laser is illustrated by Figure 11a. This spectrum contains three components, a fixed center wavelength λ_o, which is the un-modulated laser wavelength, as well as two modulation sidebands, which are at shorter wavelengths, λ_{FM-}, and longer wavelengths, λ_{FM+}. The selector 35 selects one of these sidebands as well as the un-modulated laser wavelength. This selection is achieved as a result of the optical-injection locking properties of the slave lasers. The two slave lasers preferably are constructed from semiconductor laser diodes. Such lasers typically have an injection locking bandwidth that is less than several GHz. By using a RF center tone that is sufficiently higher in frequency than this injection locking bandwidth, the modulation sidebands of the master laser 23 are spaced farther away from the un-modulated laser wavelength (and from each other) than the injection locking bandwidth of the slave lasers 70, 72. Thus each slave laser can be locked only to one of the three components of the master laser emission spectrum. One slave laser 70 (laser number 1) has its free-running wavelength selected to match the un-modulated master laser wavelength. The other slave laser 72 (laser number 2) can be tuned to select either one of the two modulation sidebands. Tuning of their drive current and/or junction temperature typically tunes the free-running wavelength of these lasers. Selection of the longer-wavelength sideband is illustrated in Figure 11b. A band selector circuit 35 controls the selection between those two sidebands.

This band selection, combined with the choice of the center frequency of the tones generated by the photonic oscillator, can be used to determine the frequency band of the final output RF waveform.

The optical signal injected into slave laser 72 actually is a single tone whose wavelength changes with time, according to the electronic frequency-modulation waveform of the RF oscillator. This change in wavelength occurs slowly compared to the relevant lifetimes associated with the optical-injection locking response of slave laser 72. These lifetimes include the effects of the photon lifetime in the optical cavity of the laser and the stimulated emission lifetime of the electronic carriers in the laser. The response of a laser often is described in terms of its relaxation-oscillation frequency. The change in wavelength of the optical injection signal is slow compared to this relaxation-oscillation frequency, which is typically on the order of GHz. Since the optical injection signal changes so slowly, it can be approximated as not changing at all. The rate at which the wavelength of the optical injected signal changes is typically between 0.1 MHz and 100 MHz, which satisfies this criterion. Injection locking of a slave laser to a frequency or wavelength modulated master laser has been investigated experimentally. This investigation by Kobayashi, Yamamoto and Kimura of NTT is described in Electronics Letters, vol 17, no.22, pp. 850-851 (1981). The authors demonstrated that so long as the excursion of the frequency or wavelength modulation is less than 20-50% of the optical-injection locking bandwidth of the slave laser, that output wavelength of that slave laser can be pulled to track the injected wavelength.

The optical signal injected into slave laser 70 is of a single constant wavelength. Slave laser 70 is preferably a device that emits in a single wavelength and is preferably a distributed feedback (DFB) laser diode. Optical injection locking of DFB lasers to single constant wavelength light is a well-characterized phenomenon.

The basic elements of the coarse-spacing comb generator are illustrated in Figure 12. In this figure the multi-tone optical comb generator 14 is depicted as taking the form of the embodiment thereof previously discussed with reference to Figure 3. However, the multi-tone optical comb generator 14 may be modified to alternatively conform to the embodiments therefore discussed with reference to 6, 9 or 10, for example.

Representative frequency spectra produced at various locations in the waveform generator are illustrated in Figure13. The single-tone, un-modulated output from slave laser 70, illustrated by Figure 13b, is fed to photonic oscillator 14. This tone is at the frequency, f_o, of the master laser 23. The photonic oscillator 14 has been described above. The output spectrum of the photonic oscillator 14 in the coarse-spacing comb generator contains a main tone at f_o and also additional oscillator tones at $f_{PO1+}, f_{PO2+}, f_{PO3+}$ and so on, as illustrated in Figure 13c. These addition tones are amplitude-modulation sidebands produced by the photonic oscillator 14. Amplitude modulation produces tones both on the high frequency side and on the low frequency side of the main tone, f_o. The set of tones ($f_{PO1-}, f_{PO2-}, f_{PO3-} \ldots$) located on the low-frequency side of the main tone is not shown in Figure 13c. The sideband optical-frequency tones are offset from the main tone by the frequency spacings of $f_{CO1+}, f_{CO2+}, f_{CO3+}$ and so on (with $f_{PO1+} - f_o = f_{CO1+}$, for example). Those frequencies $f_{CO1+}, f_{CO2+}, f_{CO3+} \ldots$ can be considered as a comb of RF tones that modulate the optical intensity modulator 32 of the photonic oscillator 14. In general, that comb has a bandwidth that is determined by the width of the bandpass filter 44. The tone spacing (equal to $f_{CO2+} - f_{CO1+}$, for example) is determined by the length of one of the fiber delay-line loops (loop 34). The bandwidth covered by these multiple tones can be quite wide, e.g. many GHz. Note that the output of slave laser 72 is also shown, by Figure 13a, and can have a Fourier spectrum with tones at the optical frequencies of $f_{FM1-}, f_{FM0}, f_{FM1+} \cdots$.

The RF-modulated lightwave signals from slave laser 72 and from the photonic oscillator 14 are combined, using an optical coupler 26, onto the same optical fiber. An optical directional coupler of the proper coupling length can be used to form two sets of combined outputs, which are carried by two output optical fibers. The optical coupler 26 is shown in Figures 2a and 11. The combined output is the desired RF-lightwave heterodyne waveform. This output will have spectral components located at four frequency regions (e.g. $f_{FM1-}, f_{FM0}, f_{FM1+} \cdots, f_{PO1+}, f_{PO2+}, f_{PO3+} \cdots, f_o$, and $f_{PO1-}, f_{PO2-}, f_{PO3-} \cdots$).

At the waveform combiner 15, optical heterodyning of two RF-modulated lightwave signals generates the desired dense frequency spread waveform. The first of the signals is produced by the photonic oscillator 14 and has multiple coarse-spaced tones. The second of the signals is produced by slave laser 72 and has a single tone whose frequency varies periodically with time, which might result in a Fourier spectrum comprising multiple fine-spaced tones. The

spacing of those fine-spaced tones are determined by the frequency modulation rate of the RF signal oscillator. The first and second signals are at different optical wavelengths. Both optical signals are directed onto at least one photodetector18, 20. The at least one photodetector 18, 20 optically heterodynes these two signals. That heterodyning process produces a mixture of sum and difference frequency components derived from these two RF-modulated lightwave signals. Some of these frequency components are in the optical range and not output by the at least one photodetector 18, 20. Others are in the RF range and most of these may be output by the at least one photodetector 18, 20 if those components are within the bandwidth of the photodetector 18, 20. One who is skilled in the art can readily derive these frequency components. Some of these components include frequencies at ($f_{PO1+} - f_{FM1+}$), ($f_{FM1+} - f_o$), ($f_{FM1+} - f_{PO1-}$), ($f_{PO1+} - f_o = f_{CO1+}$), and ($f_{PO1+} - f_{PO1-} = 2f_{CO1+}$).

Two groups of heterodyne components represent dense spread tones that are produced by interleaving the fine-spaced tones of the first RF-lightwave signal with the coarse-spaced tones of the second RF-lightwave signal. One of these two groups contains the components: ($f_{PO1+} - f_{FM1+}$), ($f_{PO1+} - f_{FM0}$), ..., ($f_{PO2+} - f_{FM1+}$), ($f_{PO2+} - f_{FM-}$), ... This group is illustrated by Figure 13d. Another group contains the components: ($f_{FM1+} - f_{PO1-}$), ($f_{FM0} - f_{PO1-}$), ..., ($f_{FM1+} - f_{PO2-}$), ($f_{FM0} - f_{PO2-}$), ... (not illustrated, but similar to Figure 13d). Preferably, a RF bandpass filter 44 is used after the at least one photodetector 18, 20 to select one of the groups of heterodyne components. The resultant, frequency spread, RF waveform represented by each group of dense spread tones has a total frequency bandwidth that is determined by the coarse-spaced multi-tone modulation from the second RF-lightwave signal and has a tone spacing that is determined by the frequency-modulation rate resulting in the first RF-lightwave signal. The fine-spaced tones are intended to be interlaced into the coarse-spaced tones and to fill in the gaps between those tones. Thus, the extent or range of their frequency modulation should preferably match the coarse tone spacing.

Additional groups of heterodyne components contain only coarse-spaced tones, only fine-spaced tones or a single frequency modulated tone. Those other groups of tones also could be useful in a sensor system. If the center frequencies of the photonic oscillator RF passband and of the frequency-modulated RF signal (input to the master laser) are chosen properly, those additional groups can be well separated from the desired dense spread tones. An example is provided below to illustrate the selection of center frequencies, bandwidths and tone

spacings. For this example, what is desired is a dense spread waveform whose frequency spectrum consists of a comb of tones with a tone spacing of 20 MHz and that covers a bandwidth of 2 GHz. This waveform is centered at 4 GHz. A second desired dense spread waveform is centered at 20 GHz. One scheme to achieve these waveforms involves modulating the frequency of a single-tone RF signal, which has a center frequency of 8 GHz. The rate of the periodic frequency modulation is 20 MHz and the total frequency excursion is 200 MHz. Note that appropriate FM waveforms can be chosen to achieve tones of uniform amplitude. When this frequency-modulated RF signal amplitude-modulates the master laser, the spacing between the center wavelength of the laser and its modulation sideband is much larger than the injection locking bandwidths of the slave lasers, which typically is 1-2 GHz. The photonic oscillator 14 has a RF bandpass filter with a center frequency of 12 GHz and a passband width of 2 GHz. This photonic oscillator 14 has the length of its optical-fiber loop set for a tone spacing of 200 MHz. The optical heterodyned output from the photodetector has spectral components located at 3-5 GHz, 7.9-8.1 GHz, 11-13 GHz, 19-21 GHz, and 23-25 GHz. The components located at 3-5 GHz and at 19-21 GHz are the dense spread carrier waveforms. The component located at 7.9-8.1 GHz is a set of fine-spaced tones. The components located at 11-13 GHz and at 23-25 GHz have only coarse-spaced tones. Note that these sets of spectral components are spaced far from each other and can be selected easily by RF bandpass elements.

Examples of the types of frequency modulated waveforms that could be generated by the apparatus of this invention are illustrated in Figure 14a – 14c. Figure 14a shows a multi-tone waveform with periodic chirp. Such waveforms have been discussed above. Another waveform, shown in Figure 14b, is a pulse that contains multiple tones that have a linear frequency modulation or chirp. Figure 14c shows a waveform containing many short segments of multi-tone chirps. A simple version of such a waveform can be constructed from the waveform of Figure 14b by dividing it into many segments and rearranging the order of those segments. Note that since the original linear FM is a single-value invertible (SVI) function, the rearranged modulation segments also comprise a SVI function. The segments can be arranged in many ways and the arrangements can differ from pulse to pulse. Also, the frequency modulation rate (e.g. the slope of the chirp) can be changed from one segment to the next. This variation of the frequency modulation rate also is illustrated in Figure 14c. The temporal durations of the segments can be different. In general, segments that have higher FM rates would be shorter. Although a linear frequency modulation is illustrated, various

frequency modulation functions could be used. The only constraint is that the functions have the SVI property.

A Receive pre-processor 110 for the type of waveform shown in Figure 14b is illustrated in Figure 15. This pre-processor has two inputs. One of the inputs is the Transmit reference 112 from the generator of Figure 2b. The other input is the Receive waveform, or the radar return signal, 114. Both the Transmit reference and the Receive waveforms could be supplied as either an electrical signal or as a RF-lightwave signal. For simplicity of illustration, the pre-processor 110 in Figure 15 is designed for waveforms that have segments of fixed duration and whose frequency modulation rate remains the same from segment to segment. The pre-processor 110 contains two tapped delay lines 116, 118, one for the reference waveform 112 and one for the Receive waveform 114. There are as many taps in a delay line as segments in a pulse. The time delay of the delay lines 116, 118 is matched to the duration of the segments. For the Receive waveform 114, each tap feeds a multi-tone comparator 120. Also, each tap is associated with a particular segment of the corresponding Transmit waveform 112. The outputs of the comparators 120 are combined to produce the compressed multi-tone pulse 128. For the reference waveform, each tap feeds a pair of switches 124, 126, which direct that tapped segment to one of the multi-tone comparators 120. Each switch 124, 126 preferably has a single pole, N throw capability, where N is the number of segments. The function of the tapped delay line 116 and switches 124, 126 for the reference waveform 112 is to present multiple time-delayed copies of a particular segment of the reference waveform to the multi-tone comparator 120 that is associated with that segment. The effect is a sliding correlator that continually compares the Receive waveform 114 with a spatially segmented version of the Transmit reference 112. Absolute synchronization of the Receive waveform 114 with the reference waveform 112 is not necessary since the reference waveform 112 is repeated every segment interval. The range ambiguity of this pre-processor is, thus, just the range associated with the duration of a segment.

In Figure 15, the paths interconnecting switches 124, 126 are shown either as a solid line or as a different style of a dashed line. These styles (solid or a particular dashed style) are also used in Figure 16 to represent different waveform segments to show the relationship between the segments and to identify in Figure 15 the switches 124, 126 corresponding to those segments.

Figure 16 depicts a multi-tone comparator 120 shown as a block in Figure 15 and also depicts the tones (or tone placeholders) on the receive and reference delay lines 114, 112. The comparator 120 includes two sets of filters 132, 134 and a set of mixers 136. One set of filters is fed the multi-tone segments of the reference waveform 112. The other set is fed the multi-tone segments of the Receive waveform 114. Those filters separate the multiple tones into individual tones or into small groups or subsets of tones. Non-selected tones ("tone placeholders") are depicted by dashed lines (having very short dashes) on the right hand side of Figure 16, with the selected tone being shown as a solid line.

Frequency selective multiplexers or directional filters could be used instead of the filters. Note, also, that the functions of these filters could be accomplished by sets of filters located at the inputs of the tapped delay lines, as discussed later. Each mixer 136 is associated with a given pair of filters, with one filter from each set. The mixers 136 mix or multiply the selected tones (or groups of tones) and determine their temporal overlap as well as their frequency difference. Those skilled in the art will realize that these parameters provide information on the object being illuminated by a radar signal. For example, the presence of temporal overlap and the time elapsed between the start of the Transmit pulse and the occurrence of that overlap provides an indication of the target range. Also, the frequencies of the mixer output tones can provide information on both the target range and its Doppler velocity. Further processing is used to derive this information. Processing of the various mixer output tones can be done by treating them separately, in separate processing circuits, or by first combining those tones together. Methods for this additional processing and combination are known in the art of radar processing and therefore are not explained in greater detail here.

The preferred characteristics of the filters 132, 134 and mixers 136 are discussed next. The relation between characteristics such as the filter bandwidth and center frequency and the frequency spacing of the multiple tones as well as the duration of a segment is discussed by considering the following example. Assume the frequency spacing between tones, Δf, is 50 MHz. The waveform has forty tones that span a range of 2 GHz. Assume that the frequency modulation is linear. The overall frequency change over the duration of a pulse is 1 GHz. The pulse duration is 100 μsec and is separated into 40 segments of 2.5-μsec duration. Thus, for each tone, the frequency change, δf, of that tone within a segment interval is 25 MHz. It is

important to keep the frequency change δf significantly smaller than the frequency spacing Δf. This allows a set of filters to separate out the different tones of a multi-tone waveform. The filter 132, 134 passband must be wider than the frequency change δf. The number of filters or mixers in a set is determined by the total frequency span, which is the span of the multi-tone waveform combined with the maximum frequency change of a given tone. For the example, this total span is 3 GHz.

In the example, the number M of filters or mixers needed per segment is sixty, for a tone spacing of 50 MHz. Also, there are 2 x N sets of filters and N sets of mixers, where N is the number of segments. A "brute-force" implementation of the present example would require 4,800 filters and 2,400 mixers. Another "brute-force" implementation separates the filtering function from the multi-tone mixing function. This implementation has M filters placed at the front of M sets of tapped delay lines to handle, separately, the Receive and reference waveform segments. The number of filters is reduced, to 2xM=120, at the expense of an increased number of tapped delay lines, from 2 to 120. Also, M-throw switches are now needed. The total number of mixers remains the same.

It might appear that the filters 132, 134 must have a single passband. Some filters may have spectrally periodic passbands. Such filters could be implemented, for example, by resonator elements or as transversal designs. For such filters to be used, it would appear that their free spectral ranges (FSR) or spectral periods should be greater than the total frequency span of the frequency-modulated multi-tone waveform (which in this example is 2+1 GHz). This requirement ensures that there is no folding or indeterminacy of the multiple tones. However, a preferred implementation of the disclosed Receiver pre-processor 110 makes use of filters that have a FSR that is smaller than the total frequency span. This implementation is illustrated in Figure 17. An important feature of this particular implementation is that the FSR of the filters 134 for the Receive waveform are different than the FSR of the filters 132 for the reference waveform. Thus, the various aliasing tones are offset in frequency from each other. This permits them to be combined later in power (incoherently) rather than in amplitude (coherently). Consider an example in which the filters 134 for the Receive waveform have a FSR of 7x40=280 MHz. Also, the filters 132 for the reference waveform have a FSR of 8x40=320 MHz. In this case, mixing of the filtered signals will create multiple tones that are separated by 50 MHz. Since their FSRs are different, each mixing tone arises

from a distinct pair of tones passed by the two spectrally periodic filters. A benefit of this approach is the reduction of filters and tapped delay lines. For example, the Receive waveform is now processed by seven filters and tapped delay lines and the reference waveform is now processed by eight filters and tapped delay lines. Thus, the total number of filters and tapped delay lines has been reduced to fifteen. Also, the number of mixers needed has been reduced to 15x40=600. The trade-off for this implementation is that the output of each mixer now has approximately eight tones. The subsequent processor must distinguish between these tones (e.g. by filtering them). Such processing of a small number of tones whose frequencies are constant is within the capability of the prior art.

The pre-processor of this invention also can process a waveform produced by periodic frequency modulation. Consider, for consistency with the above example, a waveform produced by a frequency modulation rate of 0.2 MHz and having a frequency excursion of 50 MHz. The period of this periodic chirp is 5 μsec. With the pre-processor of this example, two segments would be contained in each temporal period of the chirp. Again, the filters should have a passband width of at least 25 MHz.

The invention has been described with reference to a number of different embodiments. Those skilled in the art will realize that there are engineering tradeoffs to be made in selecting a particular embodiment (or a modification thereof) for a particular application. For example, in radar applications, those skilled in the art will realize that the frequency modulated embodiments will enjoyed improved range resolution but at the same time will experience poorer phase noise, meaning that slower moving objects are more difficult to detect.

Having described the invention in connection with a preferred embodiment therefore, modification will now certainly suggest itself to those skilled in the art. As such, the invention is not to be limited to the disclosed embodiments except as required by the appended claims.

Claims:

1. A frequency agile spread spectrum waveform generator comprising:

(a) a photonic oscillator comprising a multi-tone optical comb generator for generating a series of RF comb lines on an optical carrier;

(b) an optical heterodyne synthesizer, the optical heterodyne synthesizer including first and second phase-locked lasers, the first laser feeding the multi-tone optical comb generator and the second laser comprising a wavelength-tunable single tone laser whose output light provides a frequency translation reference; and

(c) a photodetector for heterodyning the frequency translation reference with the series of RF comb lines on the optical carrier generated by the photonic oscillator to generate an agile spread spectrum waveform.

2. The frequency agile spread spectrum waveform generator of claim 1 wherein the photonic oscillator comprises multiple loops including:

(i) a first optical delay line in a first loop for spacing a comb generated by the multi-tone optical comb generator;

(ii) a second optical delay in a second loop line for noise reduction, the second delay line being longer than the first optical delay line;

(iii) at least one photodetector connected to the first and second delay lines; and

(iv) an optical intensity modulator in a loop portion common to the first and second loops for driving the first and second optical delay lines.

3. The frequency agile spread spectrum waveform generator of claim 2 wherein the loop common portion further includes an amplifier and a band pass filter.

4. The frequency agile spread spectrum waveform generator of claim 3 wherein the amplifier is an electronic amplifier.

5. The frequency agile spread spectrum waveform generator of claim 2 wherein the loop common portion further includes a band pass filter and wherein at least one of the first and second loops includes an optical amplifier therein.

6. The frequency agile spread spectrum waveform generator of claim 2 further including means for compensating for environmental changes affecting an optical delay of at least one of the first and second optical delay lines.

7. The frequency agile spread spectrum waveform generator of claim 6 wherein the means for compensating for environmental changes affecting the optical delay of at least one of the first and second optical delay lines comprises an apparatus for adjusting a length and/or an optical refractive index of at least one of the first and second optical delay lines and a feedback circuit including a tone selection filter to the loop common portion and a mixer for mixing the output of the tone selection filter with a reference signal, an output of the mixer being operatively coupled to the adjusting apparatus.

8. The frequency agile spread spectrum waveform generator of claim 7 wherein the tone selection filter is coupled to the optical intensity modulator.

9. The frequency agile spread spectrum waveform generator of claim 8 wherein the optical intensity modulator is electro-absorption modulator having an electrical output coupled to the tone selection filter

10. The frequency agile spread spectrum waveform generator of claim 7 wherein the adjusting apparatus adjusts the length and/or the optical refractive index of both of the first and second optical delay lines.

11. The frequency agile spread spectrum waveform generator of claim 6 wherein the means for compensating for environmental changes affecting the length of at least one of the first and second optical delay lines comprises a phase shifter disposed in the loop common portion and a feedback circuit including a tone selection filter coupled to the loop common portion and a mixer for mixing the output of the tone selection filter with a reference signal, an output of the mixer being operatively coupled to the phase shifter.

12. The frequency agile spread spectrum waveform generator of claim 11 wherein the tone selection filter is coupled to the optical intensity modulator.

13. The frequency agile spread spectrum waveform generator of claim 12 wherein the optical intensity modulator is an electro-absorption modulator having an electrical output coupled to the tone selection filter.

14. The frequency agile spread spectrum waveform generator of claim 2 further including a injection seeding circuit for seeding the photonic oscillator.

15. The frequency agile spread spectrum waveform generator of claim 2 wherein the second optical delay line is more than 40 times longer than is the first optical delay line.

16. The frequency agile spread spectrum waveform generator of claim 2 further including an optical intensity modulator, the optical intensity modulator being responsive to an RF input signal and to the series of RF comb lines on the optical carrier generated by the photonic oscillator for generating a optical signal which is applied to said photodetector.

17. The frequency agile spread spectrum waveform generator of claim 2 further including an optical coupler responsive to an RF input signal, the optical coupler being connected to receive the series of RF comb lines on the optical carrier generated by the photonic oscillator and the frequency translation reference generated by the second laser, the optical coupler being connected either upstream or downstream of the optical intensity modulator which is responsive to the RF input signal.

18. The frequency agile spread spectrum waveform generator of claim 17 wherein the RF input signal includes a pulsed code or polyphased codes.

19. The frequency agile spread spectrum waveform generator of claim 1 wherein the wavelength tunable single tone laser is hopped between two different wavelengths whereby the frequency translation reference is a frequency hopped translation reference.

20. The frequency agile spread spectrum waveform generator of claim 19 wherein the optical heterodyne synthesizer includes a multi-line master laser for frequency locking the first and second lasers.

21. The frequency agile spread spectrum waveform generator of claim 20 wherein the two different wavelengths between which the wavelength tunable single tone laser is hopped correspond to two different lines of the master laser.

22. The frequency agile spread spectrum waveform generator of claim 21 wherein which the wavelength tunable single tone laser has a free-running wavelength between said two different wavelengths and wherein a LO selector controls the free-running wavelength of the wavelength tunable single tone laser.

23. The frequency agile spread spectrum waveform generator of claim 19 wherein the optical heterodyne synthesizer includes a phase-locked loop for phase-locking the first and second lasers.

24. The frequency agile spread spectrum waveform generator of claim 23 wherein the phase-locked loop includes an optical coupler, a photodetector, a phase detector and a frequency tunable RF oscillator reference arranged in said loop.

25. The frequency agile spread spectrum waveform generator of claim 24 wherein the frequency tunable RF oscillator reference produces an output that is hopped between two different frequencies and wherein a free-running wavelength of the wavelength tunable single tone laser is thereby hopped between two different wavelengths.

26. The frequency agile spread spectrum waveform generator of claim 24 wherein the loop further includes a frequency divider and wherein the phase detector in the loop is an electronic mixer.

27. The frequency agile spread spectrum waveform generator of claim 26 further including a LO selector for selecting (i) the free-running wavelength of the wavelength tunable single tone laser, (ii) the frequency of the tunable RF oscillator reference and (iii) a divide ratio of the frequency divider in the loop.

28. The frequency agile spread spectrum waveform generator of claim 19 wherein the series of RF comb lines has a bandwidth in which all of the comb line exist and wherein a

difference between the frequencies corresponding to the two different wavelengths between which the wavelength tunable single tone laser is hopped is greater than said bandwidth.

29. The frequency agile spread spectrum waveform generator of claim 19 wherein the series of RF comb lines has a bandwidth in which all of the comb line exist and wherein a difference between the frequencies corresponding to the two different wavelengths between which the wavelength tunable single tone laser is hopped is equal to or less than said bandwidth.

30. A method of generating a frequency agile spread spectrum waveform, the method comprising the steps of:

(a) generating multi-tone optical comb as a series of RF comb lines on a first optical carrier;

(b) generating a wavelength-tunable single tone or multi-tone frequency translation reference from a second optical carrier; and

(c) optically combining the optical comb with the frequency translation reference to generate a lightwave waveform suitable for subsequent heterodyning.

31. The method of claim 30 further including the step of heterodyning the lightwave waveform.

32. The method of claim 31 further wherein the step of heterodyning is performed by at least one photodetector.

33. The method of claim 30 wherein the multi-tone optical comb is generated by a photonic oscillator and further including the following steps:

(i) optically delaying the comb in a first loop for spacing comb lines in the comb;

(ii) optically delaying the comb in a second loop line for noise reduction, a second optical delay caused by step (ii) being longer than a first optical delay caused by step (i);

(iii) photodetecting the delayed comb; and

(iv) using the delayed comb in an optical intensity modulator to modulate an output of a laser to thereby generate said multi-tone optical comb as a series of RF comb lines on the first optical carrier.

34. The method of claim 33 wherein a loop common portion further includes an amplifier for amplifying the comb and a band pass filter for establishing a bandwidth of the comb.

35. The method of claim 34 wherein the amplifying is performed electronically.

36. The method of claim 33 wherein a loop common portion includes a band pass filter for establishing a band width of the comb and further including a step of optically amplifying the comb in at least one of the first and second loops.

37. The method of claim 33 further including the step of compensating for environmental changes by changing the amount of at least one of the first and second optical delays.

38. The method of claim 37 wherein the step of compensating for environmental changes by changing an amount of at least one of the optical delays is performed by comparing frequency or phase of one comb line in the comb with a reference and adjusting a length and/or an optical refractive index of at least one optical delay line carrying the comb.

39. The method of claim 38 wherein the adjusting step adjusts the length and/or an optical refractive index of first and second optical delay lines.

40. The method of claim 37 wherein the step of compensating for environmental changes by changing an amount of at least one of the optical delays is performed by comparing frequency or phase of one comb line in the comb with a reference and adjusting a phase of the comb.

41. The method of claim 33 further including the step of seeding the photonic oscillator to initiate the comb.

42. The method of claim 33 wherein the second optical delay is more than 40 times longer than is the first optical delay.

43. The method of claim 30 further including the step of intensity modulating the comb with an optical intensity modulator responsive to an RF input signal and to the series of RF comb lines on the optical carrier for modulating said lightwave waveform.

44. The method of claim 43 wherein the RF input signal applies a pulsed code or polyphased codes to the optical intensity modulator.

45. The method of claim 30 further including the step of modulating the intensity of the comb and the frequency translation reference with an optical intensity modulator responsive to an RF input signal and to the series of RF comb lines on the optical carrier and to the frequency translation reference for modulating said lightwave waveform.

46. The method of claim 45 wherein the RF input signal applies a pulsed code or polyphased codes to the optical intensity modulator.

47. The method of claim 30 wherein step (b) includes providing two slave lasers and optically injection locking the two slave lasers to an amplitude modulated master laser, the amplitude modulated master laser being driven by a frequency-modulated signal.

48. The method of claim 47 wherein an output of the master laser comprises an optical carrier and at least one amplitude modulation sideband the frequency of the sideband being modulated in response to the frequency-modulated signal.

49. The method of claim 48 wherein one of the two slave lasers is a single tone laser that is optically injection locked to the optical carrier produced by the master laser.

50. The method of claim 49 wherein the other of the two slave lasers is a variable tone laser that is optically injection locked to one of the at least one amplitude modulation sidebands produced by the master laser.

51. The method of claim 50 wherein the multi-tone optical comb is generated by a photonic oscillator and further including the following steps:

(i) optically delaying the comb in a first loop for spacing comb lines in the comb;

(ii) optically delaying the comb in a second loop line for noise reduction, a second optical delay caused by step (ii) being longer than a first optical delay caused by step (i);

(iii) photodetecting the delayed comb; and

(iv) using the delayed comb in an optical intensity modulator to modulate an output of the single tone laser to thereby generate said multi-tone optical comb as a series of RF comb lines on the first optical carrier.

52. The method of claim 47 wherein the frequency-modulated signal is a single value invertible function.

53. The method of claim 47 wherein the single value invertible function is non-continuous.

54. A frequency-modulated spread spectrum waveform generator comprising:

(a) a frequency modulated comb generator for generating a frequency modulated optical waveform;

(b) a comb generator for generating an optical comb;

(c) an optical coupler combining frequency modulated optical waveform and the optical comb; and

(d) at least one photodetector for heterodyning the output of the optical coupler.

55. The frequency-modulated spread spectrum waveform generator of claim 54 wherein the frequency modulated comb generator comprises multiple loops including:

(i) a first optical delay line in a first loop for spacing a comb generated by the multi-tone optical comb generator;

(ii) a second optical delay in a second loop line for noise reduction, the second delay line being longer than the first optical delay line;

(iii) at least one photodetector connected to the first and second delay lines; and

(iv) an optical intensity modulator in a loop portion common to the first and second loops for driving the first and second optical delay lines.

56. The frequency-modulated spread spectrum waveform generator of claim 55 wherein the loop common portion further includes an amplifier and a band pass filter.

57. The frequency-modulated spread spectrum waveform generator of claim 56 wherein the amplifier is an electronic amplifier.

58. The frequency-modulated spread spectrum waveform generator of claim 55 wherein the loop common portion further includes a band pass filter and wherein at least one of the first and second loops includes an optical amplifier therein.

59. The frequency-modulated spread spectrum waveform generator of claim 55 further including means for compensating for environmental changes affecting an optical delay of at least one of the first and second optical delay lines.

60. The frequency-modulated spread spectrum waveform generator of claim 59 wherein the means for compensating for environmental changes affecting the optical delay of at least one of the first and second optical delay lines comprises an apparatus for adjusting the length and/or an optical refractive index of at least one of the first and second optical delay lines and a feedback circuit including a tone selection filter to the loop common portion and a mixer for mixing the output of the tone selection filter with a reference signal, an output of the mixer being operatively coupled to the length adjusting apparatus.

61. The frequency-modulated spread spectrum waveform generator of claim 60 wherein the tone selection filter is coupled to the optical intensity modulator.

62. The frequency-modulated spread spectrum waveform generator of claim 61 wherein the optical intensity modulator is electro-absorption modulator having an electrical output coupled to the tone selection filter

63. The frequency-modulated spread spectrum waveform generator of claim 60 wherein the adjusting apparatus adjusts the length and/or an optical refractive index of both of the first and second optical delay lines.

64. The frequency-modulated spread spectrum waveform generator of claim 59 wherein the means for compensating for environmental changes affecting the length of at least one of the first and second optical delay lines comprises a phase shifter disposed in the loop common portion and a feedback circuit including a tone selection filter coupled to the loop common portion and a mixer for mixing the output of the tone selection filter with a reference signal, an output of the mixer being operatively coupled to the phase shifter.

65. The frequency-modulated spread spectrum waveform generator of claim 64 wherein the tone selection filter is coupled to the optical intensity modulator.

66. The frequency-modulated spread spectrum waveform generator of claim 65 wherein the optical intensity modulator is an electro-absorption modulator having an electrical output coupled to the tone selection filter.

67. The frequency-modulated spread spectrum waveform generator of claim 55 further including a injection seeding circuit for seeding the photonic oscillator.

68. The frequency-modulated spread spectrum waveform generator of claim 55 wherein the second optical delay line is more than 40 times longer than is the first optical delay line.

69. The frequency-modulated spread spectrum waveform generator of claim 55 further including an optical intensity modulator, the optical intensity modulator being responsive to an RF input signal and to the series of RF comb lines on the optical carrier generated by the photonic oscillator for generating a optical signal which is applied to said photodetector.

70. The frequency-modulated spread spectrum waveform generator of claim 55 further including an optical coupler responsive to an RF input signal, the optical coupler being connected to receive the series of RF comb lines on the optical carrier generated by the photonic oscillator and the frequency translation reference generated by the second laser, the optical coupler being connected either upstream or downstream of the optical intensity modulator which is responsive to the RF input signal.

71. The frequency-modulated spread spectrum waveform generator of claim 70 wherein the RF input signal includes a pulsed code or polyphased codes.

72. The frequency-modulated spread spectrum waveform generator of claim 54 wherein the frequency modulated comb generator comprises two slave lasers and an amplitude modulated master laser for optically injection locking the two slave lasers to the amplitude modulated master laser, the amplitude modulated master laser being driven by a frequency-modulated signal.

73. The frequency-modulated spread spectrum waveform generator of claim 72 wherein an output of the master laser comprises an optical carrier and at least one amplitude modulation sideband the frequency of the sideband being modulated in response to the frequency-modulated signal.

74. The frequency-modulated spread spectrum waveform generator of claim 73 wherein one of the two slave lasers is a single tone laser that is optically injection locked to the optical carrier produced by the master laser.

75. The frequency-modulated spread spectrum waveform generator of claim 74 wherein the other of the two slave lasers is a variable tone laser that is optically injection locked to one of the at least one amplitude modulation sidebands produced by the master laser.

76. The frequency-modulated spread spectrum waveform generator of claim 75 wherein the optical comb is generated by a photonic oscillator comprising:

(i) means for optically delaying the comb in a first loop for spacing comb lines in the comb;

(ii) means for optically delaying the comb in a second loop line for noise reduction, a second optical delay caused the second loop being longer than a first optical delay caused by the first loop;

(iii) means for photodetecting the delayed comb; and

(iv) an optical intensity modulator for modulating an output of the single tone laser to thereby generate said multi-tone optical comb as a series of RF comb lines on an optical carrier.

77. The frequency-modulated spread spectrum waveform generator of claim 72 wherein the frequency-modulated signal is a single value invertible function.

78. The frequency-modulated spread spectrum waveform generator of claim 77 wherein the single value invertible function is non-continuous.

79. A method of generating a spread spectrum waveform, the method comprising the steps of:

(a) generating multi-tone optical comb as a series of RF comb lines on a first optical carrier;

(b) generating a wavelength-tunable optical frequency translation reference from a second optical carrier; and

(c) heterodyning the optical comb and the optical frequency translation reference to generate the spread spectrum waveform.

80. The method of claim 79 wherein the wavelength-tunable optical frequency translation reference comprises a frequency modulated single sideband optical signal.

81. The method of claim 80 further wherein the step of heterodyning is performed by at least one photodetector.

82. The method of claim 81 wherein the multi-tone optical comb is generated by a photonic oscillator and further including the following steps:

(i) optically delaying the optical comb in a first loop for spacing RF comb lines in the comb;

(ii) optically delaying the comb in a second loop line for noise reduction, a second optical delay caused by step (ii) being longer than a first optical delay caused by step (i);

(iii) photodetecting the delayed comb; and

(iv) using the delayed comb in an optical intensity modulator to modulate an output of a laser to thereby generate said multi-tone optical comb as a series of RF comb lines on an optical carrier.

83. The method of claim 82 wherein a loop common portion further includes an amplifier for amplifying the comb and a band pass filter for establishing a bandwidth of the comb.

84. The method of claim 83 wherein the amplifying step is performed electronically.

85. The method of claim 82 wherein a loop common portion includes a band pass filter for establishing a band width of the comb and further including a step of optically amplifying the comb in at least one of the first and second loops.

86. The method of claim 82 further including the step of compensating for environmental changes by changing the amount of at least one of the first and second optical delays.

87. The method of claim 86 wherein the step of compensating for environmental changes by changing an amount of at least one of the optical delays is performed by comparing frequency or phase of one comb line in the comb with a reference and adjusting a length and/or an optical refractive index of at least one optical delay line carrying the comb.

88. The method of claim 87 wherein the adjusting step adjusts the length and/or an optical refractive index of first and second optical delay lines.

89. The method of claim 86 wherein the step of compensating for environmental changes by changing an amount of at least one of the optical delays is performed by comparing frequency or phase of one comb line in the comb with a reference and adjusting a phase of the comb.

90. The method of claim 82 further including the step of seeding the photonic oscillator to initiate the comb.

91. The method of claim 82 wherein the second optical delay is more than 40 times longer than is the first optical delay.

92. The method of claim 79 further including the step of intensity modulating the comb with an optical intensity modulator responsive to an RF input signal and to the series of RF comb lines on the optical carrier for modulating said lightwave waveform.

93. The method of claim 92 wherein the RF input signal applies a pulsed code or polyphased codes to the optical intensity modulator.

94. The method of claim 93 wherein the spread spectrum waveform is a frequency modulated multi-tone waveform suitable for a radar system.

95. The method of claim 79 further including the step of modulating the intensity of the comb and the frequency translation reference with an optical intensity modulator responsive

to an RF input signal and to the series of RF comb lines on the optical carrier and to the frequency translation reference for modulating said spread spectrum waveform.

96. The method of claim 95 wherein the RF input signal applies a pulsed code or polyphased codes to the optical intensity modulator.

97. The method of claim 79 wherein step (b) includes providing two slave lasers and optically injection locking the two slave lasers to an amplitude modulated master laser, the amplitude modulated master laser being driven by a frequency-modulated signal.

98. The method of claim 97 wherein an output of the master laser comprises an optical carrier and at least one amplitude modulation sideband the frequency of the sideband being modulated in response to the frequency-modulated signal.

99. The method of claim 98 wherein one of the two slave lasers is a single tone laser that is optically injection locked to the optical carrier produced by the master laser.

100. The method of claim 99 wherein the other of the two slave lasers is a variable tone laser that is optically injection locked to one of the at least one amplitude modulation sidebands produced by the master laser.

101. The method of claim 100 wherein the multi-tone optical comb is generated by a photonic oscillator and further including the following steps:

(i) optically delaying the comb in a first loop for spacing comb lines in the comb;

(ii) optically delaying the comb in a second loop line for noise reduction, a second optical delay caused by step (ii) being longer than a first optical delay caused by step (i);

(iii) photodetecting the delayed comb; and

(iv) using the delayed comb in an optical intensity modulator to modulate an output of the single tone laser to thereby generate said multi-tone optical comb as a series of RF comb lines on the first optical carrier.

102. The method of claim 97 wherein the frequency-modulated signal is a single value invertible function.

103. The method of claim 102 wherein the single value invertible function is non-continuous.

104. A frequency-modulated spread spectrum waveform generator comprising:

(a) a frequency modulated comb generator for generating a relatively fine-spaced optical comb;

(b) a comb generator for generating a relatively coarse-spaced optical comb;

(c) an optical coupler combining the relatively fine-spaced optical comb and the relatively coarse-spaced optical comb; and

(d) at least one photodetector for heterodyning the output of the optical coupler.

105. A receiver pre-processor for pulse compression of multi-tone received and reference waveforms, the pre-processor comprising:

means for temporal division of the multi-tone received and reference waveforms into series of temporal segments;

means for repeatedly comparing multiple time-staggered sets of the segments of the reference multi-tone waveform with the segments of the received multi-tone waveform.

106. The receiver pre-processor of claim 105 wherein the means for temporal division of the multi-tone received and reference waveforms into series of segments comprises first and second tapped delay lines, with each delay line being associated with one of the received and reference waveforms and having a series of taps corresponding to the number of temporal segments of the associated one of the received and reference waveforms.

107. The receiver pre-processor of claim 106 wherein the means for repeatedly comparing multiple time-staggered sets of the segments of the reference multi-tone waveform with the segments of the received multi-tone waveform comprises comparators and switches, the taps of the delay line associated with receive waveform each feeding one of said comparators and the taps of the delay line associated with reference waveform each feeding, via a pair of said switches, a switch-selected one of the comparators to thereby present multiple time-delayed copies of a particular segment of the reference waveform to a comparator that is associated with that segment for continually comparing the received multi-tone waveform with a spatially segmented version of the reference multi-tone waveform.

108. The receiver pre-processor of claim 107 wherein the comparators each include at least one filter to spectrally separate multiple tones of the reference multi-tone waveform and received multi-tone waveform for comparison by RF mixing.

109. The receiver pre-processor of claim 108 wherein comparison by the comparators occurs either on a tone-by-tone basis or with subsets of tones.

110. The receiver pre-processor of claim 108 wherein the filters have a periodic frequency spectrum, the filters comprising two sets of filters with each set having a different spectral period.

111. A method of generating a dense-spectrum waveform comprising the steps of:
   i. generating a frequency comb of relatively fine-spaced tones;
   ii. generating a frequency comb of relatively coarse-spaced tones; and
   iii. interleaving the fine-spaced tones and the coarse-spaced tones by optical heterodyning.

112. The method of claim 111 wherein the relatively fine-spaced tones are generated by a wavelength-tunable laser having a period frequency variation.

113. The method of claim 112 wherein the relatively coarse-spaced tones are generated by a photonic oscillator comprising a multi-tone comb generator for generating a series of RF comb lines on an optical carrier.

114. The method of claim 113 wherein the interleaving of the relatively fine-spaced tones and the relatively coarse-spaced tones is accomplished by using a photodetector to optically heterodyne an output of the wavelength-tunable laser with an output of the photonic oscillator.

115. The method of claim 114 further including means for intensity and/or phase modulating the dense spread-spectrum waveform to thereby produce a pulse coded or polyphase waveform suitable for a radar system.

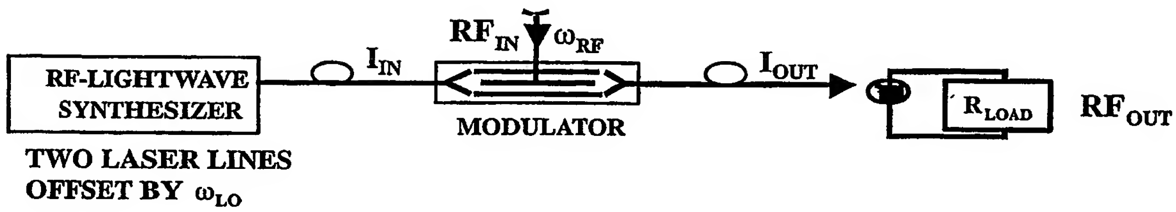


Figure 1 prior art

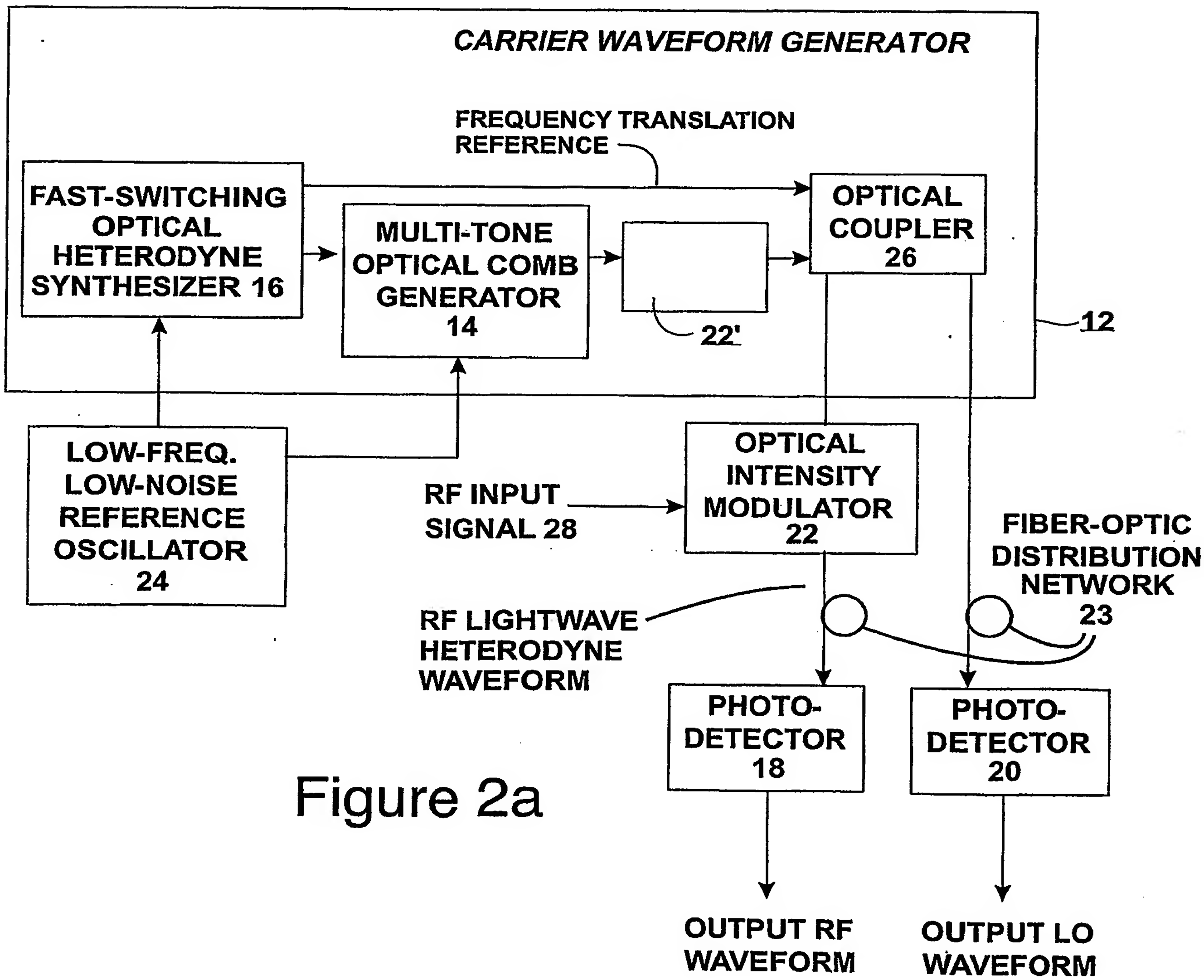


Figure 2a

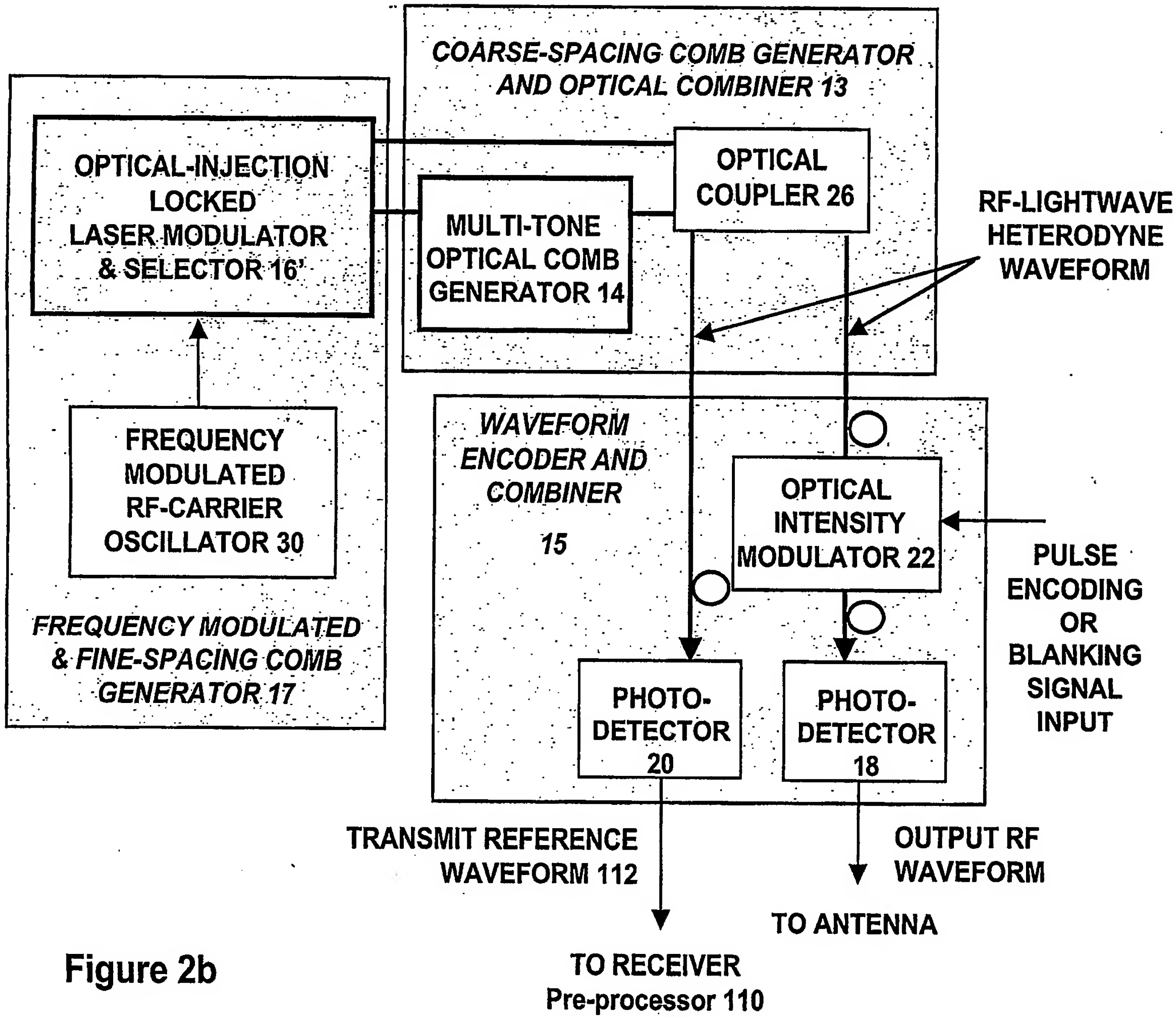

COARSE-SPACING COMB GENERATOR AND OPTICAL COMBINER 13
OPTICAL-INJECTION LOCKED LASER MODULATOR & SELECTOR 16'
MULTI-TONE OPTICAL COMB GENERATOR 14
OPTICAL COUPLER 26
RF-LIGHTWAVE HETERODYNE WAVEFORM
FREQUENCY MODULATED RF-CARRIER OSCILLATOR 30
FREQUENCY MODULATED & FINE-SPACING COMB GENERATOR 17
WAVEFORM ENCODER AND COMBINER 15
OPTICAL INTENSITY MODULATOR 22
PULSE ENCODING OR BLANKING SIGNAL INPUT
PHOTO-DETECTOR 20
PHOTO-DETECTOR 18
TRANSMIT REFERENCE WAVEFORM 112
OUTPUT RF WAVEFORM
TO ANTENNA
TO RECEIVER Pre-processor 110

Figure 2b

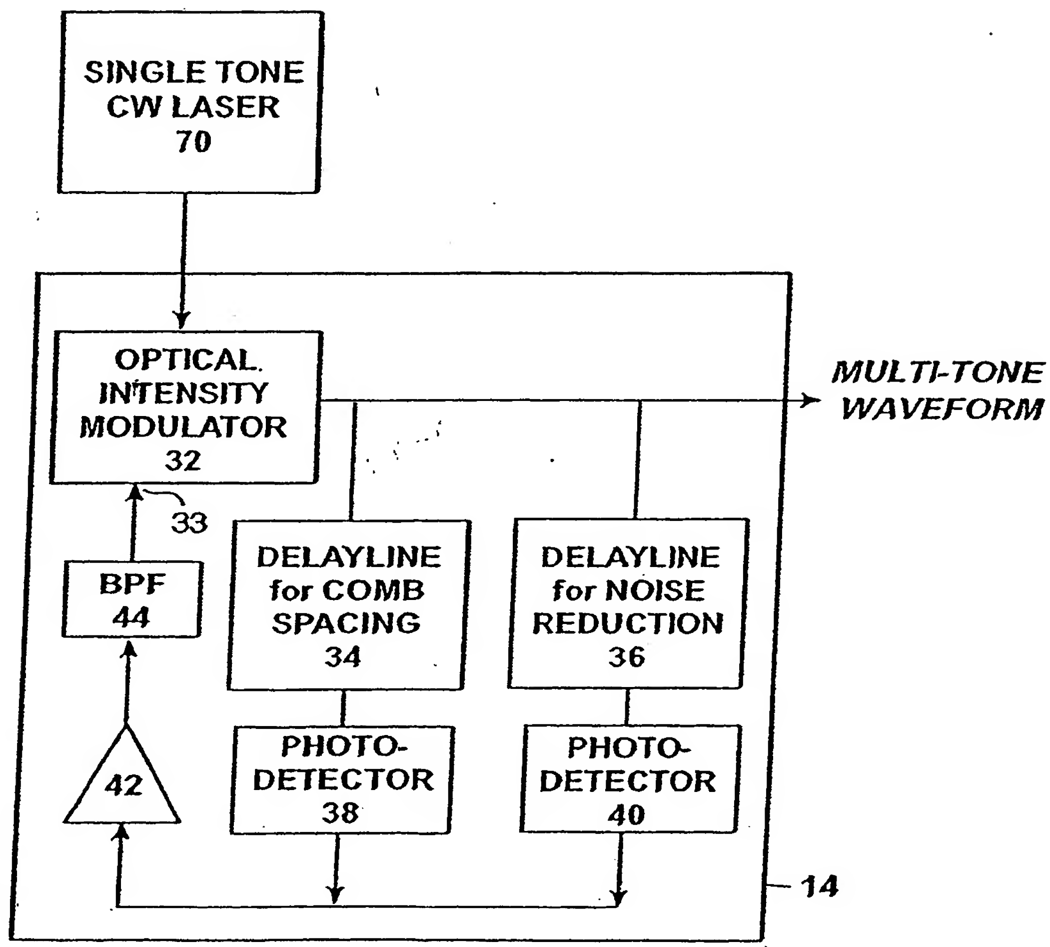
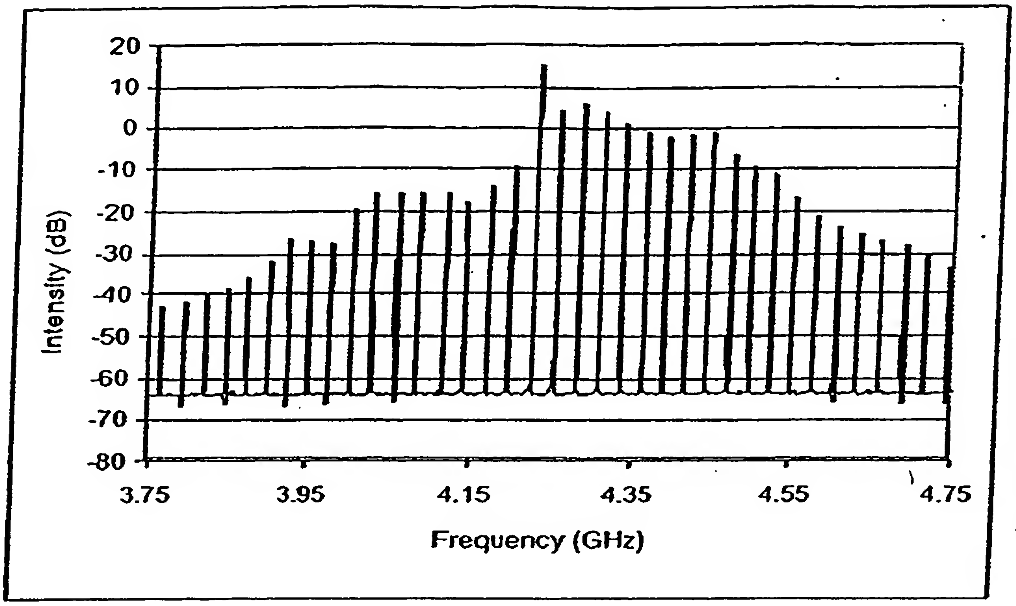
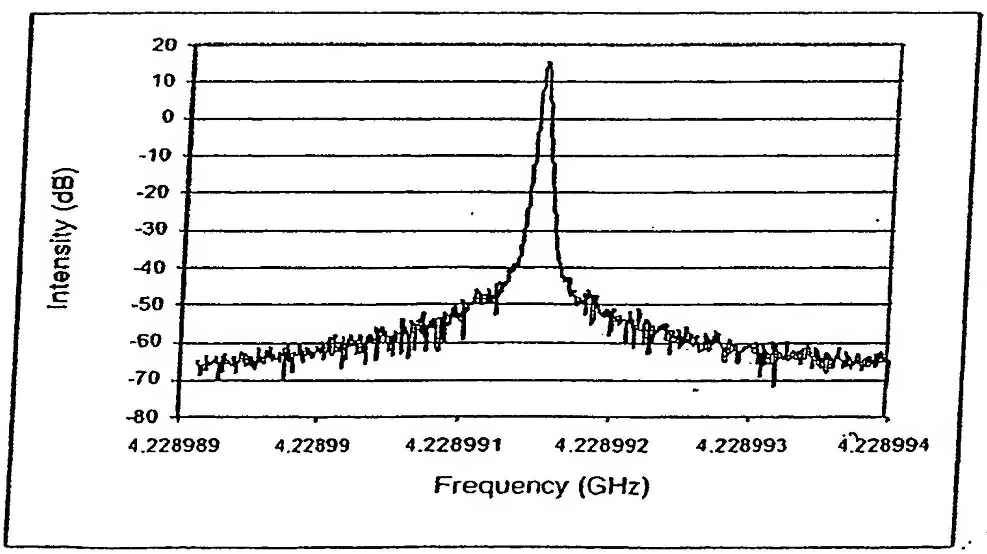

SINGLE TONE
CW LASER
70
OPTICAL
INTENSITY
MODULATOR
32
33
MULTI-TONE
WAVEFORM
BPF
44
DELAYLINE
for COMB
SPACING
34
DELAYLINE
for NOISE
REDUCTION
36
42
PHOTO-
DETECTOR
38
PHOTO-
DETECTOR
40
14

Figure 3



RBW = 100 KHz
VBW = 1 KHz
SPN = 1 GHz
SWP = 30 s
L_{F1} < 10 m
L_{F2} = 1 km
BPF = 4(1) GHz

Figure 4



RBW = 30 Hz
VBW = 3 Hz
SPN = 5 KHz
SWP = 150 s
L_{f1} < 10 m
L_{f2} = 1 km
BPF = 4(1) GHz

Figure 5

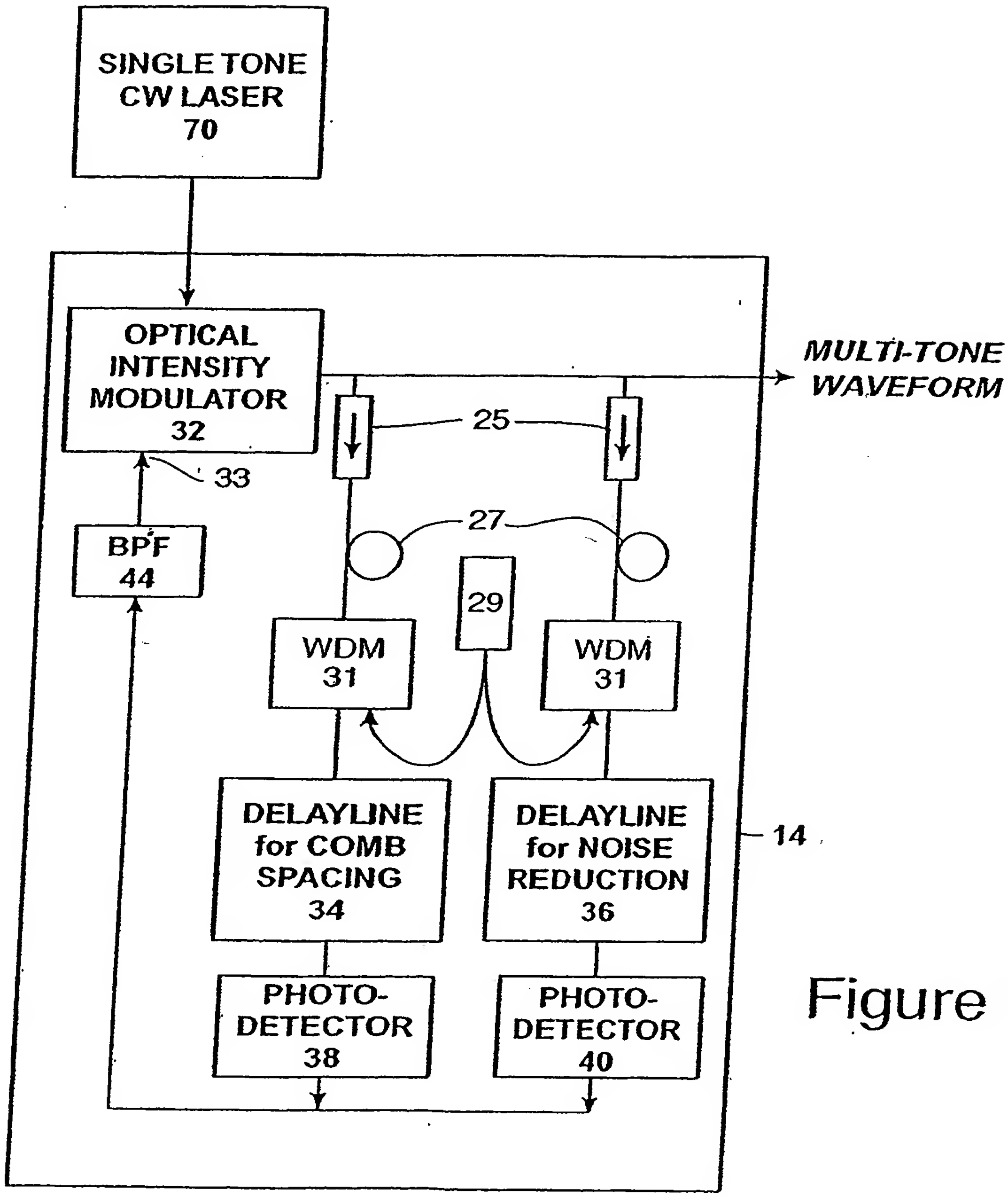

SINGLE TONE
CW LASER
70
OPTICAL
INTENSITY
MODULATOR
32
MULTI-TONE
WAVEFORM
25
33
27
BPF
44
29
WDM
31
WDM
31
DELAYLINE
for COMB
SPACING
34
DELAYLINE
for NOISE
REDUCTION
36
14
PHOTO-
DETECTOR
38
PHOTO-
DETECTOR
40

Figure 6

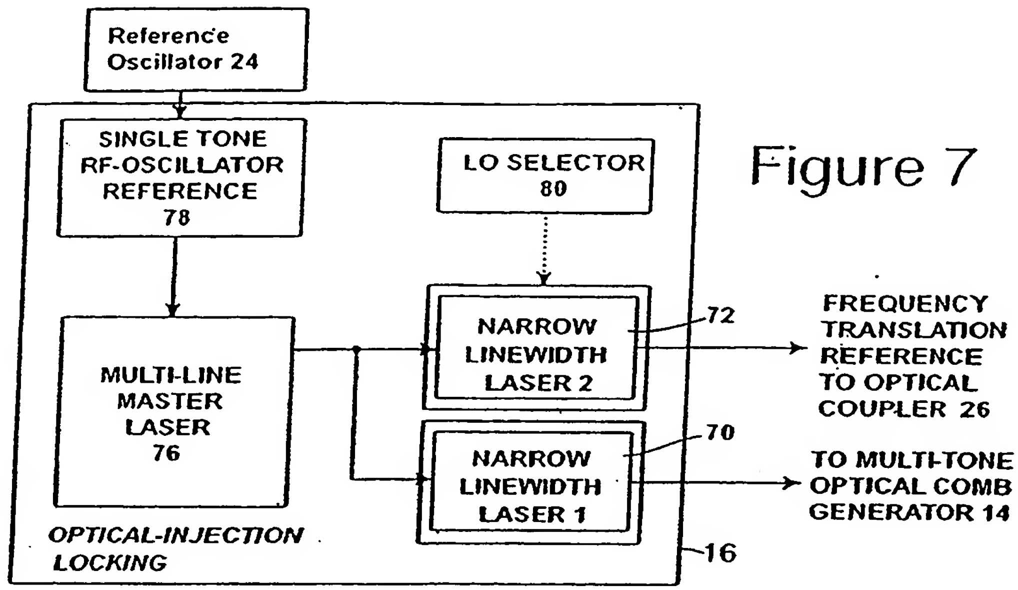


Figure 7

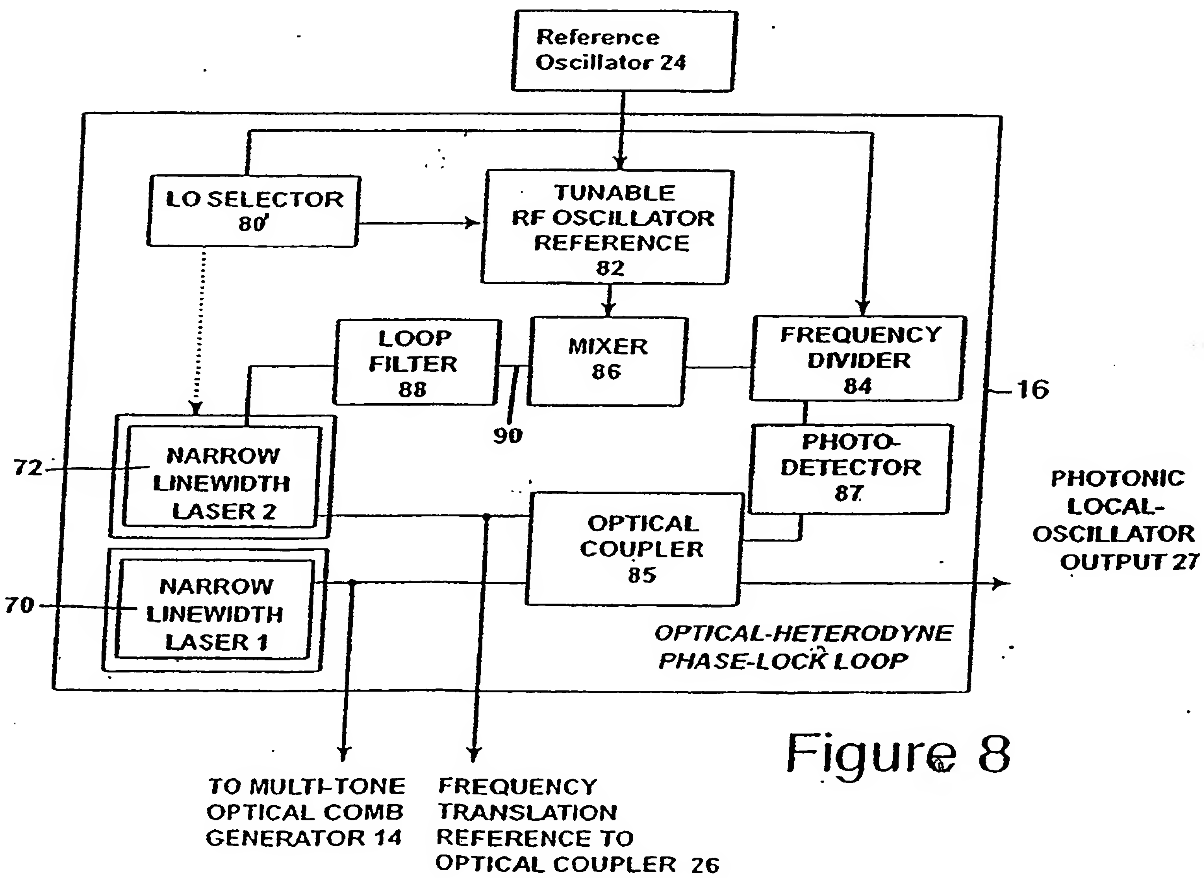


Figure 8

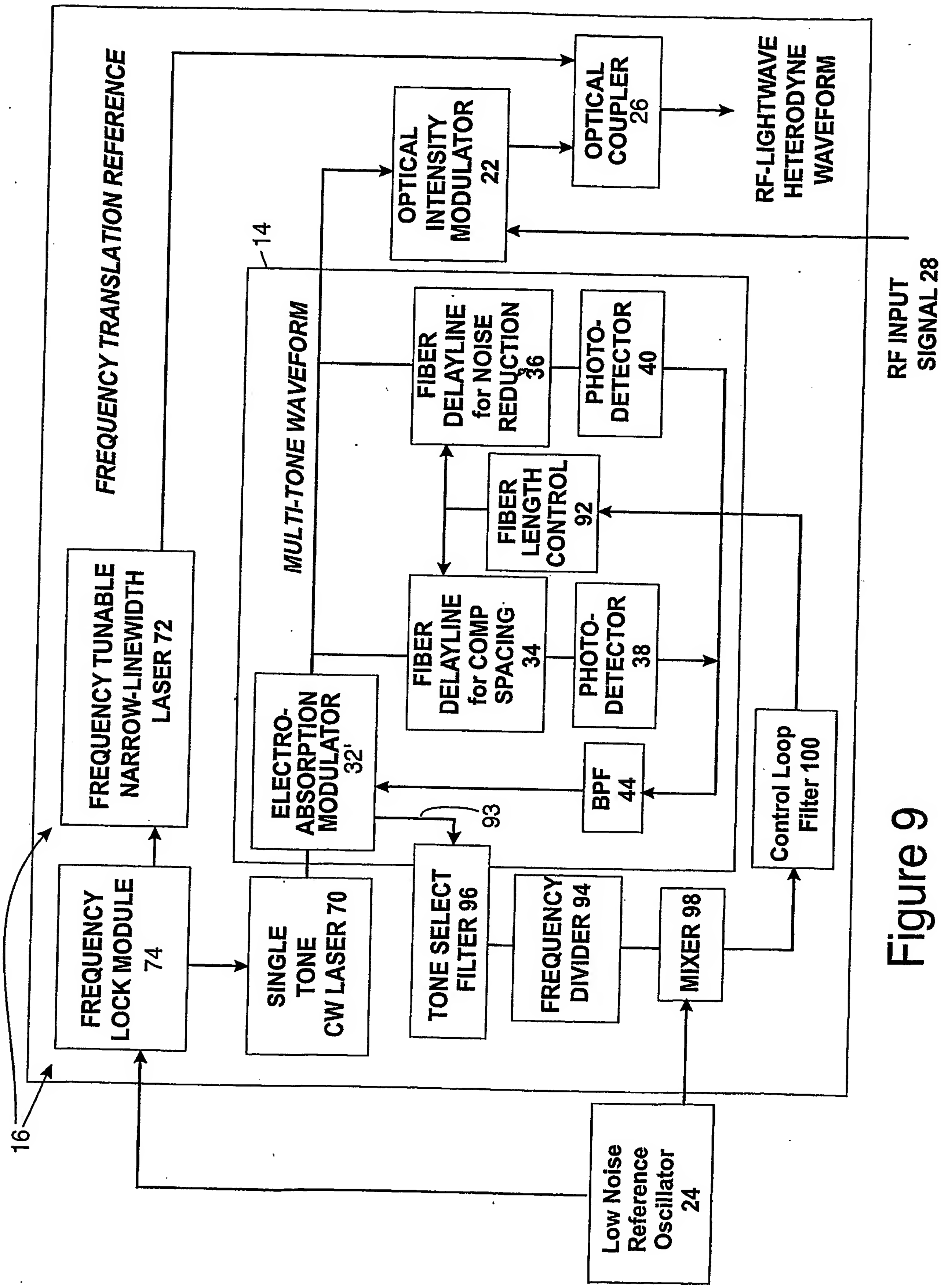

FREQUENCY TRANSLATION REFERENCE
OPTICAL COUPLER 26
OPTICAL INTENSITY MODULATOR 22
RF-LIGHTWAVE HETERODYNE WAVEFORM
14
MULTI-TONE WAVEFORM
FIBER DELAYLINE for NOISE REDUCTION 36
PHOTO-DETECTOR 40
RF INPUT SIGNAL 28
FIBER LENGTH CONTROL 92
FREQUENCY TUNABLE NARROW-LINEWIDTH LASER 72
FIBER DELAYLINE for COMP SPACING 34
PHOTO-DETECTOR 38
ELECTRO-ABSORPTION MODULATOR 32'
BPF 44
Control Loop Filter 100
93
FREQUENCY LOCK MODULE 74
SINGLE TONE CW LASER 70
TONE SELECT FILTER 96
FREQUENCY DIVIDER 94
MIXER 98
16
Low Noise Reference Oscillator 24

Figure 9

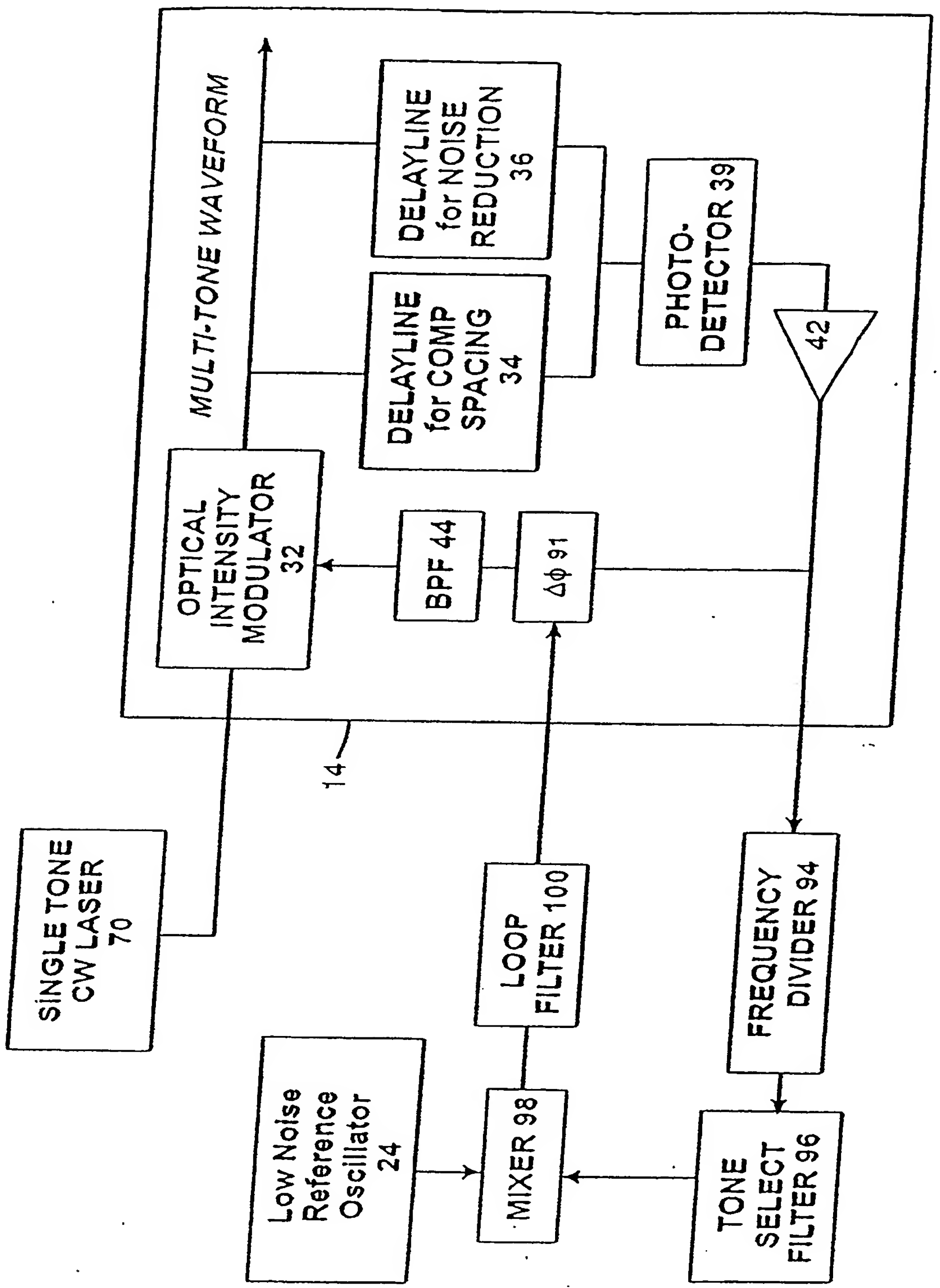

MULTI-TONE WAVEFORM
DELAYLINE for NOISE REDUCTION 36
DELAYLINE for COMP SPACING 34
PHOTO-DETECTOR 39
42
OPTICAL INTENSITY MODULATOR 32
BPF 44
Δϕ 91
14
SINGLE TONE CW LASER 70
LOOP FILTER 100
FREQUENCY DIVIDER 94
Low Noise Reference Oscillator 24
MIXER 98
TONE SELECT FILTER 96

Figure 10

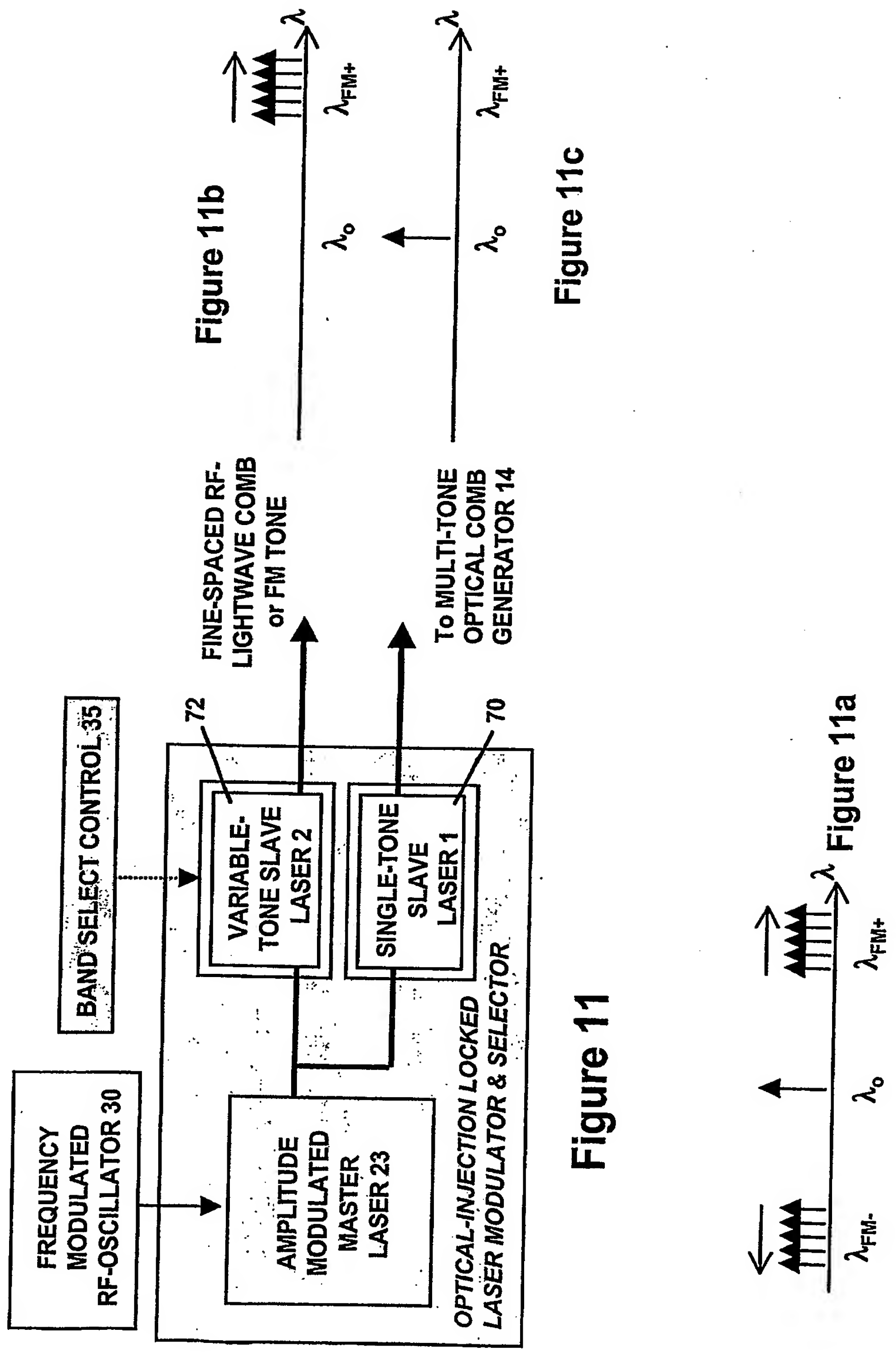


Figure 11

Figure 11a

Figure 11b

Figure 11c

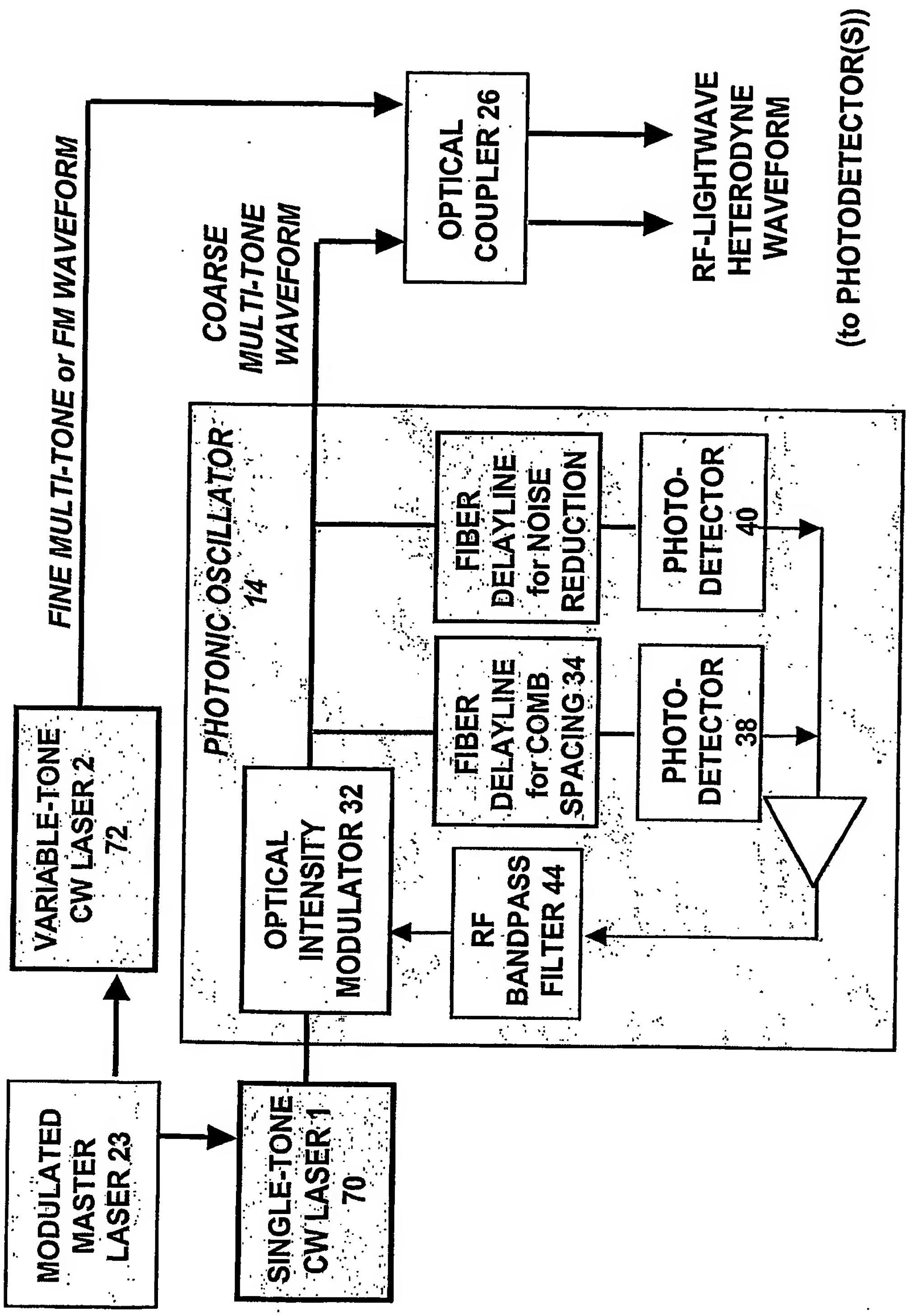

MODULATED MASTER LASER 23
SINGLE-TONE CW LASER 1 70
VARIABLE-TONE CW LASER 2 72
FINE MULTI-TONE or FM WAVEFORM
PHOTONIC OSCILLATOR 14
OPTICAL INTENSITY MODULATOR 32
RF BANDPASS FILTER 44
FIBER DELAYLINE for COMB SPACING 34
FIBER DELAYLINE for NOISE REDUCTION
PHOTO-DETECTOR 38
PHOTO-DETECTOR 40
COARSE MULTI-TONE WAVEFORM
OPTICAL COUPLER 26
RF-LIGHTWAVE HETERODYNE WAVEFORM
(to PHOTODETECTOR(S))

Figure 12

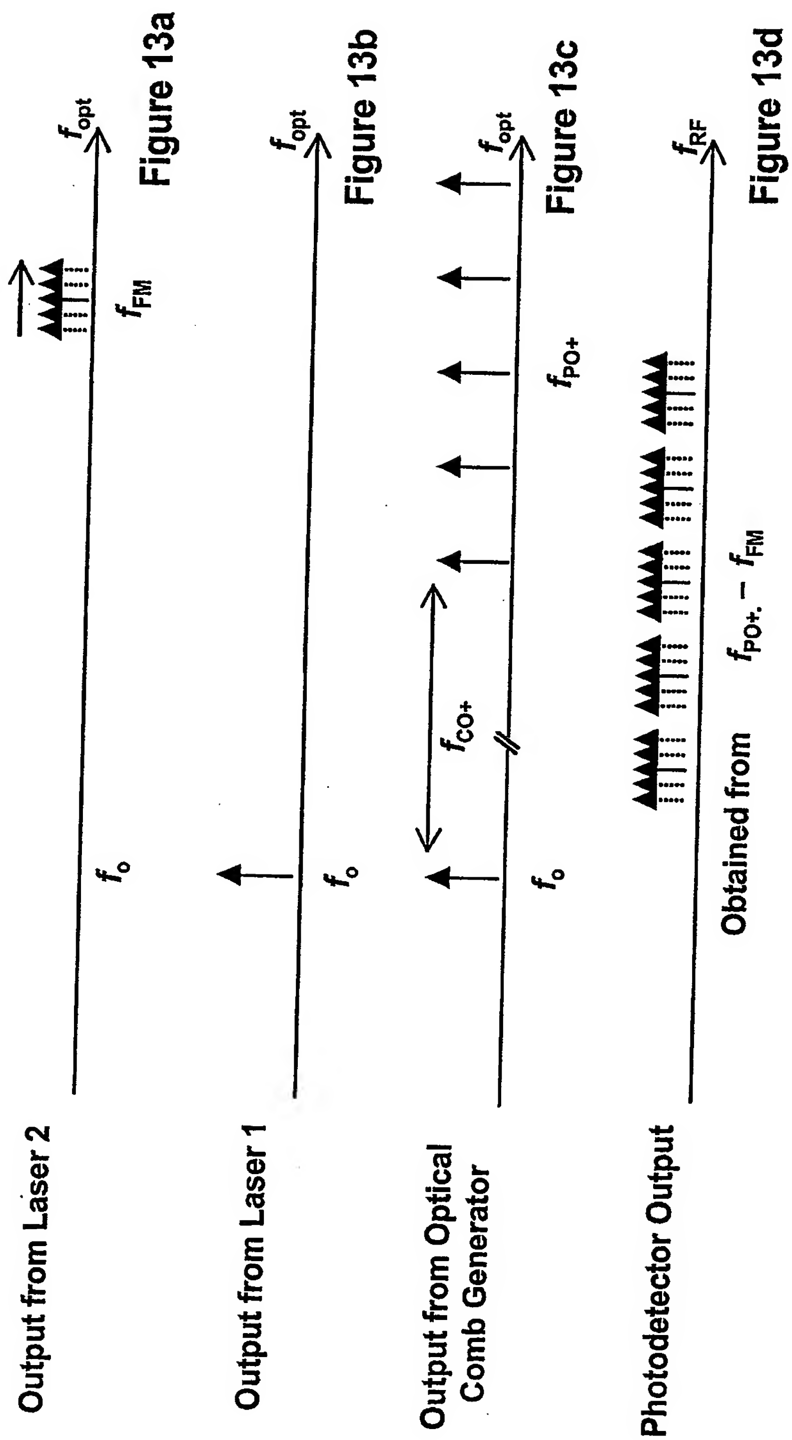


Figure 13a

Figure 13b

Figure 13c

Figure 13d

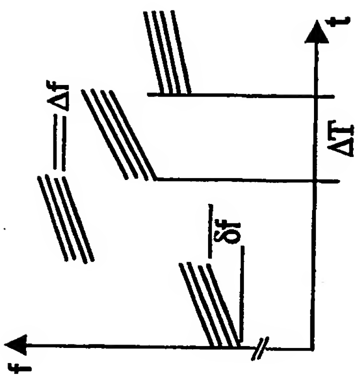


Figure 14c

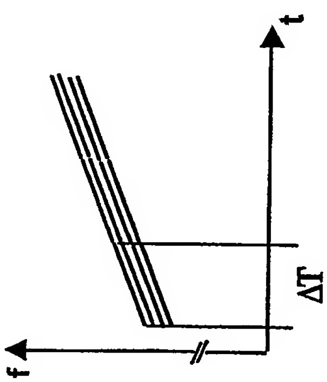


Figure 14b

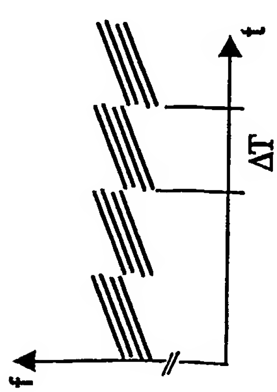


Figure 14a

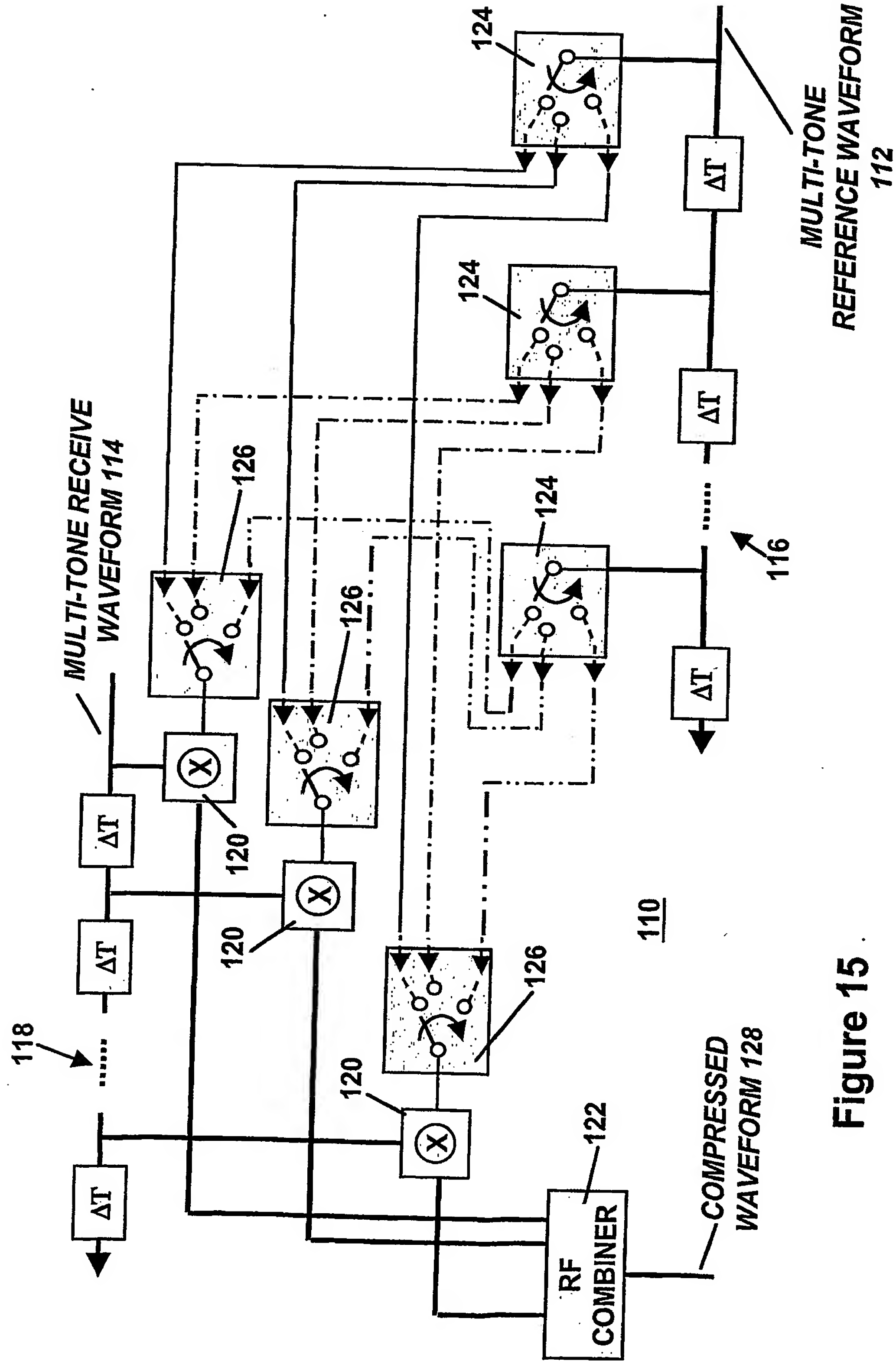

MULTI-TONE REFERENCE WAVEFORM 112
MULTI-TONE RECEIVE WAVEFORM 114
124
124
124
126
126
126
120
120
120
ΔT
ΔT
ΔT
ΔT
ΔT
ΔT
116
118
110
RF COMBINER
122
COMPRESSED WAVEFORM 128

Figure 15

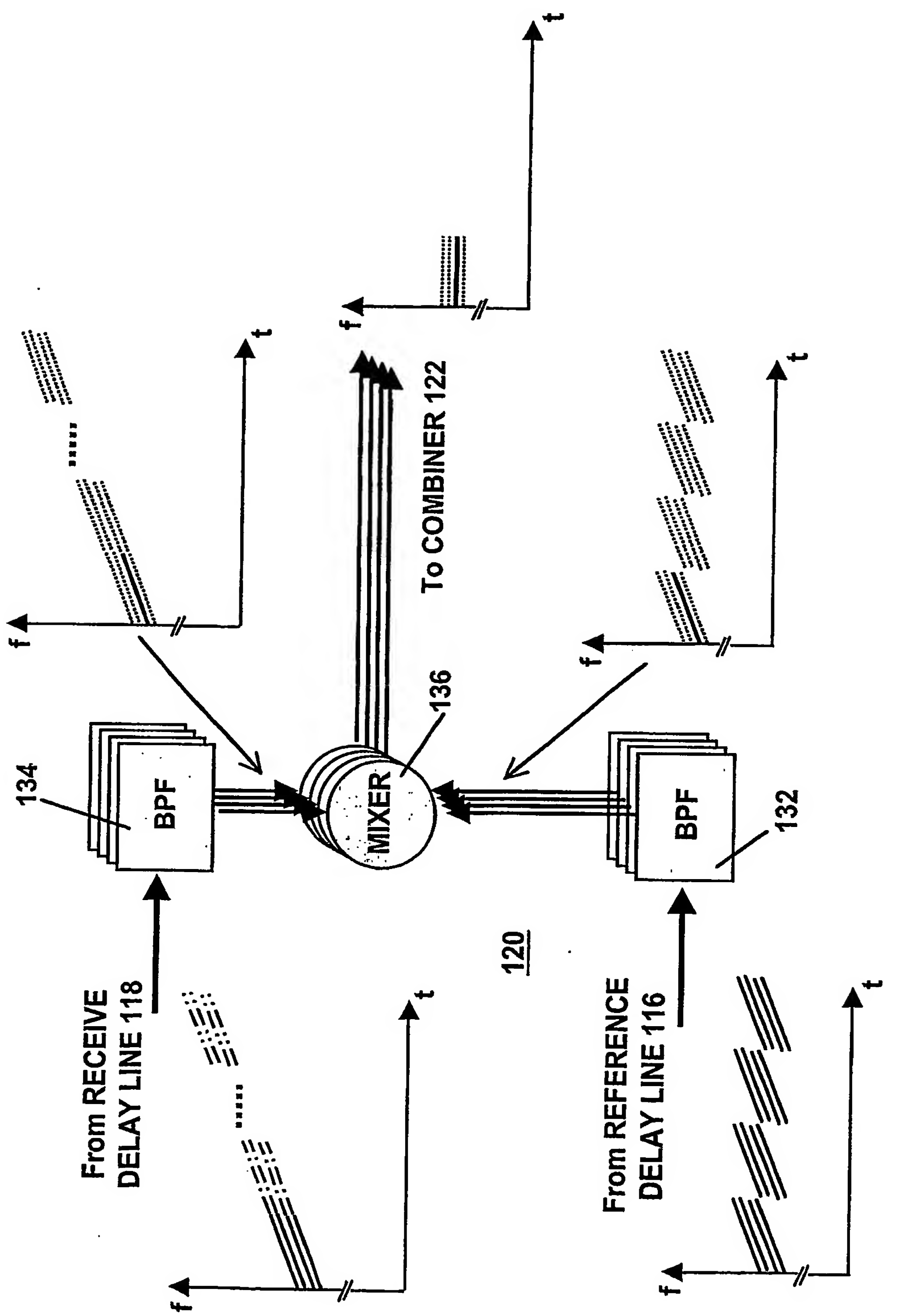

From RECEIVE DELAY LINE 118
BPF
134
MIXER
136
To COMBINER 122
BPF
132
From REFERENCE DELAY LINE 116
120
f
t

Figure 16

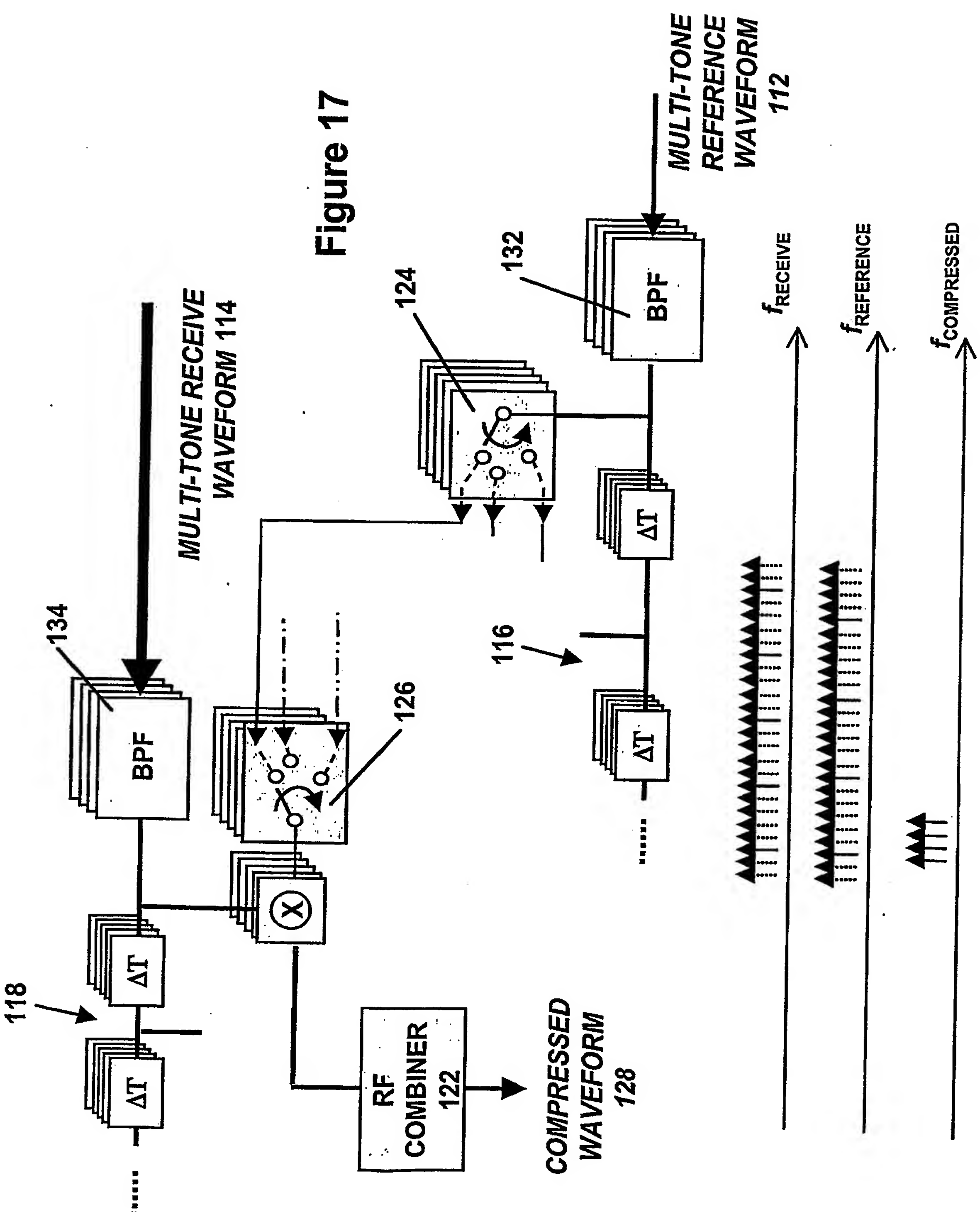

MULTI-TONE RECEIVE WAVEFORM 114
MULTI-TONE REFERENCE WAVEFORM 112
134
BPF
132
BPF
124
126
116
118
ΔT
ΔT
ΔT
ΔT
X
RF COMBINER 122
COMPRESSED WAVEFORM 128
$f_{RECEIVE}$
$f_{REFERENCE}$
$f_{COMPRESSED}$

Figure 17